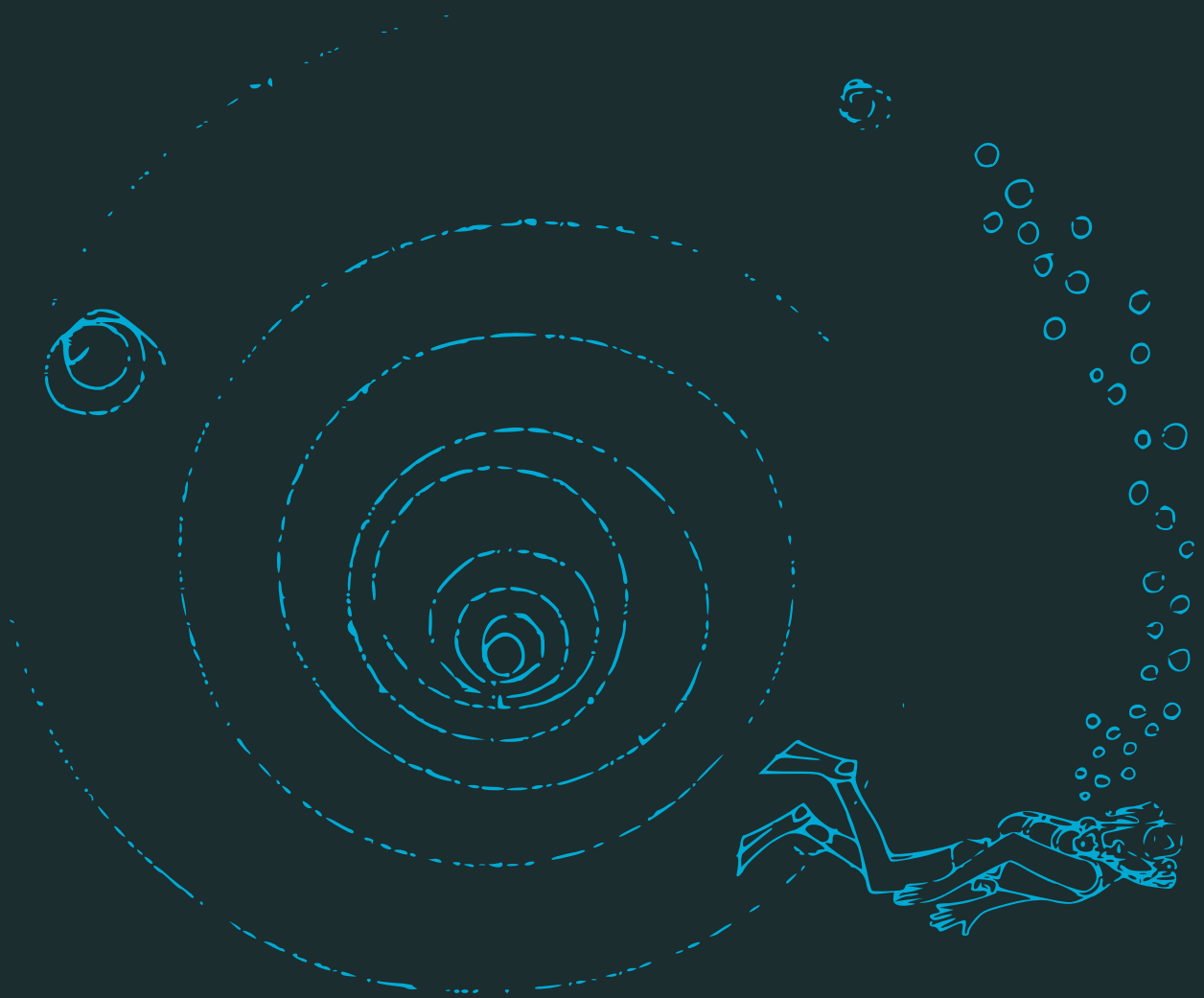




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IS FUN

An introductory course for secondary schools in four volumes

BOOK FOUR

Jim Jardine, *B.Sc., M.Ed., A.Inst.P.*

Head of the Physics Department, George Watson's College, Edinburgh

Illustrated by Geoffrey Salter



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Preface

Contents

This volume, which covers Sections 10, 11 and 12 of the Scottish physics syllabus, completes a four-year elementary course.

Primarily a pupil's book, this is intended to be used under the direction of a teacher. Experimental details are given for both teacher and pupil, and suppliers of apparatus are indicated by numerical subscripts which refer to a list of names and addresses given at the back of the book. Nuffield equipment is used throughout and subscripts beginning with the letter N indicate the Nuffield apparatus number.

Demonstrations and *Experiments* cover the basic course, and optional practical tasks are included as *Projects* and *Practical Puzzles*. *Projects* can be carried out as individual or group activities in the lab if time permits. Some can be done at home and others are suitable for science clubs or open days. *Practical Puzzles* can be considered simply as problems or they can be used as practical exercises yielding results which can be analysed.

So that this book may be suitable for pupils going on to Higher Grade work, additional material has been included as *Optional Extras*. This material is not necessary for O Grade examinations. Chapter 13 is essentially an optional extra and could perhaps best be considered as a reading exercise for abler pupils.

As in the first three volumes, alternative experiments or demonstrations are often given to allow teachers to make as much use as possible of available equipment. Obviously no pupil should be expected to work through every experiment or every problem, but only the teacher can decide what material is appropriate to any particular class.

Apparatus

Pupil experiments have been designed to use as little apparatus as possible. For example, only one basic meter (2–0–10 mA) is needed. If the Unilab version is used, three plug-in units (1 A d.c., 5 V/20 V d.c., 10 mA/5 V a.c.) will cover all the experiments in this book. Only one inductor (Unilab 250/5000 turns) and three resistors (150 Ω , 600 Ω , and 1.8 M Ω) are used for pupil experiments. The resistors and other components such as capacitors (ranging from 0.1–5000 μ F) may be conveniently mounted between 4 mm sockets on small wooden boxes (MK3890) available cheaply from Messrs Wootton & Co. Ltd., Alma Works, Ponders End, Middlesex.

Expense and time can often be saved by setting up a number of different experiments round the laboratory. The pupils can then move from one 'station' to another doing each experiment in

turn. Some sections, for example mechanical oscillations, lend themselves readily to this treatment.

Thanks

This book has been produced with the co-operation and encouragement of so many people that I find it impossible adequately to express my thanks for all the help received. Friends and colleagues from the physics departments of several schools and colleges read the manuscript and made many helpful comments and criticisms.

I am particularly grateful to our lab technician for designing and making prototype apparatus, to the illustrators and the artist, Geoffrey Salter, for his patience and skill in interpreting the spirit of the new syllabus and to the publishers for their enthusiasm and guidance throughout the undertaking.

The entire manuscript was read and criticised by Dr S. Davidson of Aberdeen University. For the time and trouble he so willingly took I should like to express my sincere thanks.

Edinburgh, August 1967

J. J.

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*The endpaper spectra were photographed by M. O. Jackson.
Imperial College of Science and Technology, University of London,*

The Electron

CHAPTER |

This book is about electrons. No matter where we go we cannot escape them. They are at the heart of matter itself as component parts of every atom. Once on the move they carry energy to do a thousand and one different jobs. They bring energy to operate our record players and washing machines, to light and heat our homes. A beam of electrons will paint a scene on a television screen or magnify an object a million times in an electron microscope. A more intense beam will drill through a sheet of stainless steel in less than a second.

During this course we have, until now, taken this tiny charge carrier for granted. Before investigating its behaviour further we ought perhaps to look at a little of its history. Was the electron discovered or invented? Is it a particle, a wave or an idea? Why is it now accepted as a useful model with which to explain electrical phenomena? By the end of the course you should be able to answer these questions.

Early History

In the 6th century before Christ, the Greek philosopher Thales discovered that a piece of amber rubbed with fur would attract tiny fragments of straw. Our modern term *electricity* comes from the Greek word for amber, which is *elektron*. During the next 2000 years little, if any, progress was made towards finding a model which would make sense of this phenomenon. At the beginning of the 18th century Isaac Newton described electricity as a 'weightless fluid', a description which was generally accepted at that time. Benjamin Franklin, about 1750, seems to have been the first person to speak of 'electrical particles' but he produced no evidence for their existence.

In 1833 Faraday discovered that when electric charges flow through an electrolyte the mass of a substance liberated depends on the total charge passed. He was able to calculate the charge/mass ratio for various substances (see Chapter 5). As a result of his work Faraday said, 'Although we know nothing of what an atom is, and though we are in equal if not greater ignorance of electricity, yet there is an immensity of *facts* which justify us in *believing* that the atoms of matter are in some way endowed with electrical powers'.

In 1871 Wilhelm Weber spoke of 'charged particles' to describe his theory of electromagnetism, and in 1881 Helmholtz quoted Faraday's evidence from electrolysis to support his own belief that electricity 'positive as well as negative is divided into definite elementary portions which behave like atoms of electricity'.

It seems then that during the 19th century the idea of charged particles gained popularity, and the results of many experiments were explained in terms of such particles. Yet it was equally possible to explain these results in terms of a kind of continuous electric juice. There was still no direct evidence for the belief in a charged particle.

Cathode Rays

We saw earlier (Book 2, page 25) that when a high voltage was applied to an evacuated tube the gas glowed and a current passed through it. The invention of a much improved vacuum pump by Henry Geissler in 1855, together with the development of good glass-to-metal seals, made possible the study of currents through *very* low pressure gas. As the pressure was reduced the gas glow in the tubes disappeared and the glass itself started to glow. This was particularly noticeable at the end of the tube opposite the cathode. It looked as if some kind of radiation was being emitted from the cathode. What was being radiated? This was the question that puzzled scientists. Some German scientists favoured the idea of a wave or ray—a kind of electromagnetic radiation—and Goldstein coined the phrase *cathode rays*. Hittorf and others showed that the rays travelled in straight lines and could be bent by a magnetic field. We used a cold cathode tube earlier (Book 2, page 134) but in the following experiment we will use a hot cathode tube which produces cathode rays with a very much lower p.d. between its anode and cathode.

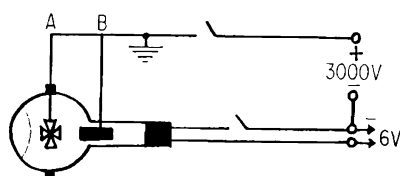


Fig. 1

Demonstration 1.1.

(i) Connect a Maltese cross tube₁ (Tel 523) to a filament and E.H.T. supply as shown (Fig. 1). Switch on the filament only and note the shadow produced. What does this tell you about light rays?

(ii) Switch on the E.H.T. supply. What happens? What does this tell you about cathode rays? Are the shadows produced by light rays and cathode rays identical in size?

(iii) Bring a bar magnet up to the side of the tube and note what happens (a) to the light shadow, (b) to the cathode ray shadow. Does this suggest that light and cathode rays are similar phenomena?

Use the rule mentioned in Book 2, page 155 to see if cathode rays behave like electrons flowing in wires.

(iv) Insert a 0–500 microammeter in the wire AB and see if charge flows. If so in what direction are the electrons moving? What happens if the wire is disconnected from the cross at A? Can you think of a possible explanation?

In England, Sir William Crookes (1879) and others devised a variety of tubes to investigate the properties of cathode rays. They found that the rays could heat a thin foil to red heat. *What does this tell you about cathode rays? (1).*

In general the English physicists seemed to think that cathode rays behaved more like a stream of particles than waves or rays. It has been suggested that the Englishman's passion for cricket may have influenced this belief! The deflection of the cathode rays by

a magnetic field could not be easily explained by the wave model, and when in 1895 the Frenchman Jean Perrin showed that cathode rays definitely carried negative charges (Book 2, page 29) the case for the particle model was strengthened still further.

J. J. Thomson (1856–1940)

In 1897 J. J. Thomson 'discovered the electron'. What exactly does this statement mean? Certainly not that the *idea* was new. The Irishman G. Johnstone Stoney had given the name *electron* to a negatively charged particle many years earlier. The fact was, however, that no-one had shown experimentally that cathode rays *were* particles. This was Thomson's contribution to the story. He showed that cathode rays not only had *charge* but also *mass*. What is more important, he was able to measure the actual charge per unit mass, that is the ratio e/m where e is the charge on the electron and m its mass. Moreover he found that this ratio remained the same with different gases in the tube and using different metals for the electrodes. J. J. Thomson was awarded the Nobel prize in physics in 1906.

As with so many other scientific discoveries, the electron was not immediately seen to have great practical significance. In fact one of the toasts at the annual dinner of the Cavendish Laboratory was 'The electron: may it never be of any use to anybody!'

Thomson's apparatus was similar to that shown in Fig. 2(b). With it Thomson was able to deflect a beam of cathode rays by an electric field and by a magnetic field. He then assumed that if the rays consisted of particles of charge e and mass m they should obey Newton's Laws of motion. By applying these laws he found the ratio e/m to be constant. You can see in the next experiment how the apparatus was used although the calculation of e/m is beyond the scope of this course.

Demonstration 1.2.

(a) Connect up the deflection tube₁ (Tel 525) as shown in Fig. 2(a). Turn the electrostatic deflecting voltage to zero so that both deflecting plates are at earth potential. Switch on the filament and E.H.T. supply and observe the undeflected beam. Why is the path of the beam made visible when the electrons strike the fluorescent screen?

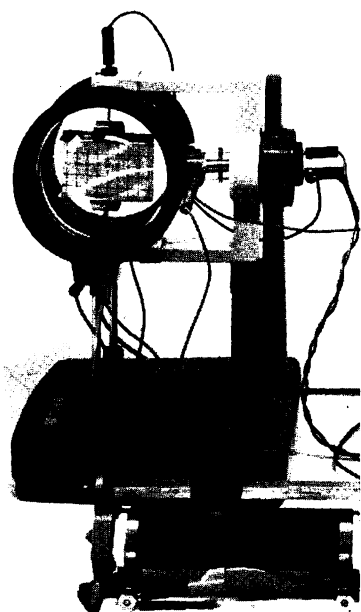


Fig. 2 (b)

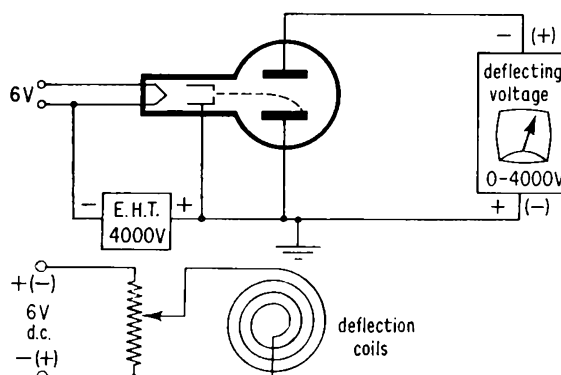


Fig. 2 (a)

Investigate the effect on the beam when (i) a strong magnet, and (ii) a charged polythene rod are brought close to the tube.

Now switch on and adjust the current through the coils so that the beam passes through a uniform magnetic field. What happens?

Switch off the current through the coils and apply a p.d. across the deflecting plates with the polarity as shown. How does the path of the cathode rays compare with the path a stone would take if it were projected horizontally through the air? (cf Book 3, page 69). Were both in a uniform field? Did the stone have mass and momentum? What does this part of the experiment suggest? What happens when the p.d. across the plates is altered? Reverse this p.d. and note the change. (If a second high voltage source is not available, deflection can be seen by connecting one plate to earth and one to the heater. The plate connections may then be reversed.)

If the accelerating (anode) voltage is reduced will the electrons travel between the parallel plates faster, slower or at the same speed as before? How will this affect the time taken for them to pass through the deflecting field? Will the beam therefore be bent more, less or the same as before?

Can you now apply both electrostatic and magnetic fields so that their effects cancel? By doing this Thomson found the ratio e/m . This ratio is approximately 1.76×10^{11} C/kg.

(b) The Leybold fine beam tube (Fig. 3) illustrates the same principles in a dramatic way. The path of the cathode rays can be seen as a faint glow in the low pressure gas (hydrogen) in the tube.

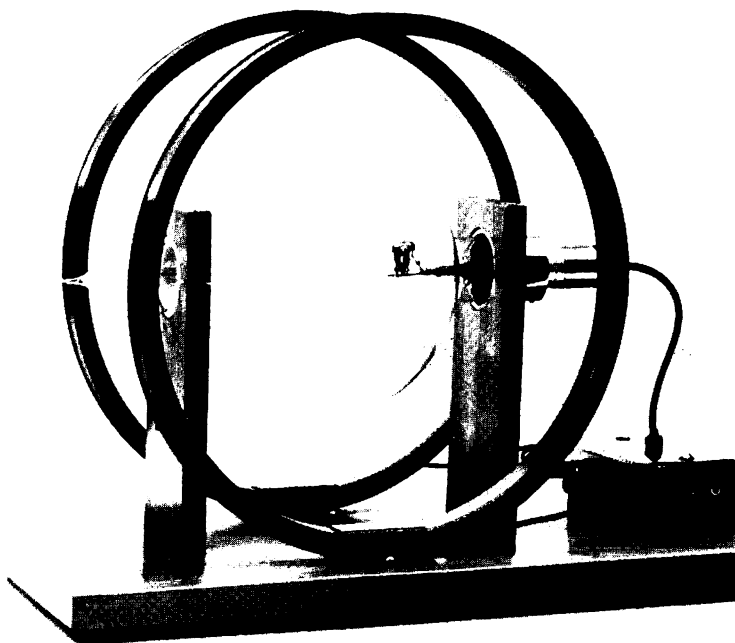


Fig. 3

Again the beam can be bent either by a p.d. across the deflecting plates or by a current through the Helmholtz coils.

The importance of Thomson's experiment lay in showing that not only was e/m the same under a variety of different conditions but also that the particles carried a charge per unit mass which was more than a thousand times greater than that carried by the lightest known ion. The charge/mass ratio for the hydrogen ion was known from Faraday's work on electrolysis. It was about 9.58×10^7 C/kg. Either the charge on the electron was very much bigger or its mass very much smaller than the hydrogen atom. Thomson believed that the latter was the case, but until someone could measure the actual charge (e) or the mass (m) the problem could not be solved.

R. A. Millikan (1868–1953)

The task of accurately measuring the charge (e) on the electron was eventually accomplished by R. A. Millikan in the early years of the 20th century. He constructed a device so sensitive that with it he could measure the small forces exerted on a tiny charged oil drop. He then altered the charge by subjecting the drop to a beam of X-rays and again measuring the force acting on it. In this way he discovered that the drop gained or lost charge only in multiples of a *basic unit of charge* which he was able to calculate. To appreciate how he did this we must first revise some basic principles.

Potential Energy and Potential Difference

For many purposes potential difference can be thought of as a kind of electrical 'pressure difference'. This is not, however, a good enough definition to enable us to treat electricity quantitatively, and we ought now to define potential difference more precisely.

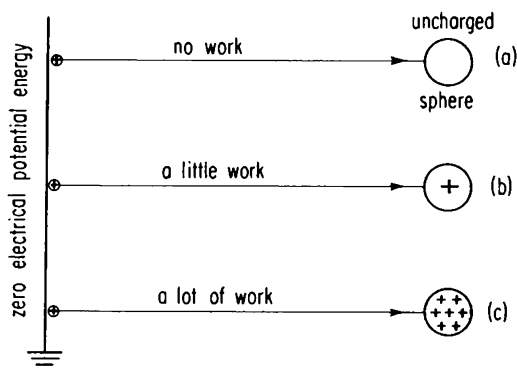


Fig. 4

Imagine that an uncharged metal sphere is situated a long way from an earthed plate as shown in Fig. 4 (a). If now we move a single positive charge from the plate to the sphere we do no work as there is no opposing force. We can safely assume that the Earth

is so large that the removal of a positive charge makes no difference. If we now move a second positive charge from the plate to the sphere there will be an opposing force, as the sphere has a positive charge on it. A little work will have to be done (Fig. 4 (b)).

The more positive charges there are on the sphere the greater will be the force repelling any newcomers. More and more work will have to be done to add each further positive charge. When work is done energy is transformed, in this case from chemical energy stored in our muscles to electrical potential energy stored on the sphere.

The greater the electrical potential energy that is stored on the sphere, the greater is the *potential difference* (p.d.) between the sphere and earth. We can, in fact, measure this p.d. by the amount of work done in moving unit charge between the earth and the sphere. When 1 joule of energy is needed to move a charge of 1 coulomb between two points, the p.d. between these points is 1 joule/coulomb, which we call 1 *volt*.

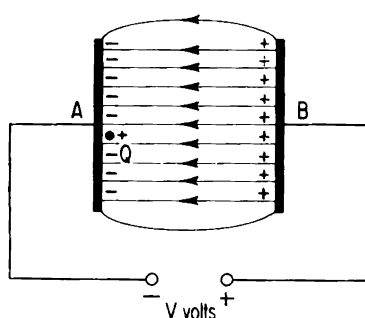


Fig. 5

$$\begin{array}{c} \text{p.d. in} \\ \text{volts} \end{array} \quad V = \frac{\begin{array}{c} \text{energy in joules} \\ E \end{array}}{\begin{array}{c} \text{charge in coulombs} \\ Q \end{array}}$$

If a positively charged particle Q is moved from plate A to plate B (Fig. 5) work has to be done against the field. If the p.d. between the plates is kept constant at 1 volt, 1 joule of work will be done on every coulomb of charge transferred.

When 1 coulomb moves across a p.d. of 1 volt the work done is 1 joule.

When Q coulombs move across a p.d. of 1 volt the work done is Q joules.

When Q coulombs move across a p.d. of V volts the work done is QV joules.

$$\begin{array}{c} \text{joules} \end{array} \quad \text{Work done} = \begin{array}{c} QV \\ \text{coulombs} \quad \text{volts} \end{array}$$

Practical Puzzle 2. The dome of a Van de Graaff generator is earthed and the motor speed adjusted until the belt is moving fairly slowly. When the earth connection is removed from the dome the motor slows down or stops. Why is this?

Problem 3. What will happen to a positively charged particle released from B (Fig. 5) if we ignore gravity? What kind of energy would it possess when it reached A? If you knew the size of V , Q and the mass of the particle how could you find its speed at A?

Problem 4. If the value of charge/mass for an electron is $1.76 \times 10^{11} \text{ C/kg}$ what velocity would it gain by being accelerated across a p.d. of 100 volts?

Electric Fields

Experiment 1.3.

(a) Electric field lines indicate the *direction* of an electric force at different points. These lines can be illustrated using the

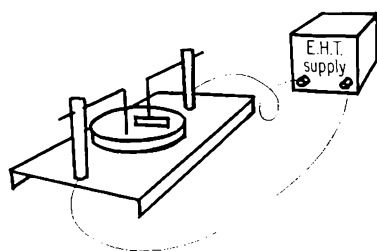


Fig. 6

apparatus_{N149} shown in Fig. 6. The necessary voltage may be obtained from a piezo-electric E.H.T. generator₂ (available unmounted₂₆), a Van de Graaff generator or E.H.T. supply.

A nonconducting liquid (castor oil, liquid paraffin, carbon tetrachloride, etc.) is contained in a petri dish and particles (cress or grass seeds, semolina, iron filings, etc.) float on top. When an electric field is applied the particles line up along the field lines. An overhead projector can be used to study the fields.

The diagrams in Fig. 7 illustrate various fields. Can you identify them?

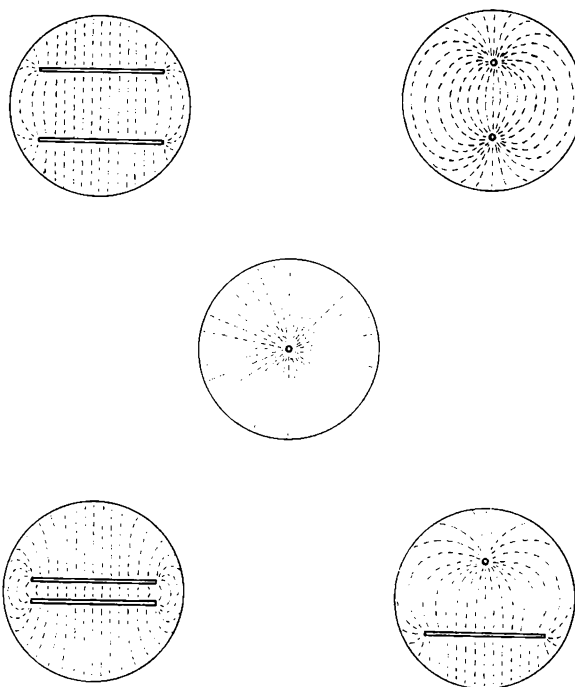


Fig. 7

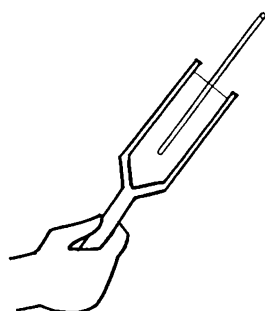


Fig. 8

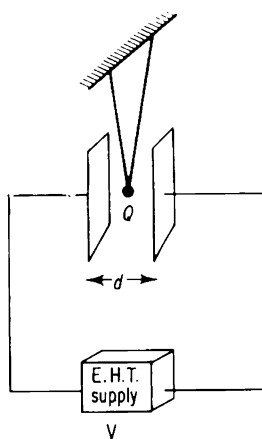


Fig. 9

(b) Alternatively, we can use threads attached to charged conductors (e.g. the dome of a Van de Graaff generator) to show the direction of the field lines.

(c) A third method of investigating electric fields makes use of an electrostatic compass. A piece of aluminium foil on a drinking straw is pivoted as shown (Fig. 8) and held by an insulator. Can you explain how this instrument enables us to find the direction of an electric field?

Force on a Charged Particle in an Electric Field

Demonstration 1.4. Suspend a charged polythene sphere (Malvern kit_{N51}) on two long nylon threads between charged plates as shown in Fig. 9. Now apply a p.d. between the plates. A displacement of the charged sphere will indicate that a force is acting on it. Small movements are easily seen if a high intensity source of light is used to project a shadow of the apparatus on a blackboard.

A commercial version of this apparatus is available₂.

(i) Vary the p.d. between the plates (V) and note how the displacement alters (Q and d constant).

(ii) Share the charge on the sphere (Q) with another similar sphere. In this way the charge is reduced. Again note the displacement (V and d constant). Copy the following statements and complete them.

(a) If the p.d. between the plates is increased the force on the sphere is . . .

(b) If the charge on the sphere is increased the force on the sphere is . . .

The force (F) acting on a charge (Q) moving from one plate to another parallel plate is constant as the field is uniform. If the plates are d metres apart the work done in moving Q coulombs from A to B (Fig. 5) is given by the product $F \times d$.

$$\begin{array}{ccccc} \text{Work done} & = & Fd & & \\ \text{joules} & & \text{newtons} & \times & \text{metres} \end{array}$$

If the p.d. between the plates is V volts the work done on a charge is also given by the product QV . We see then that work done $= Fd = QV$.

$$\begin{array}{ccccc} \text{Work done} & = & Fd & = & QV \\ & & \text{newtons} & \times & \text{metres} \\ & & & & \text{coulombs} \times \text{volts} \end{array}$$

Models of Millikan's Experiment

Demonstration 1.5. In these experiments you can study the forces between two parallel plates. A transparent plastic food box (about $24 \times 12 \times 8$ cm) with aluminium foil glued inside the base and the lid is ideal. A Van de Graaff generator is used to supply a p.d. across the plates and this can be varied by moving the belt of the generator slowly by hand.

(If the belt is inaccessible, use a string potentiometer. One end of the string is attached to the dome and the other to the base. The end of the wire from the top plate of the box is then slid up and down the string to vary the p.d. across the plate.)

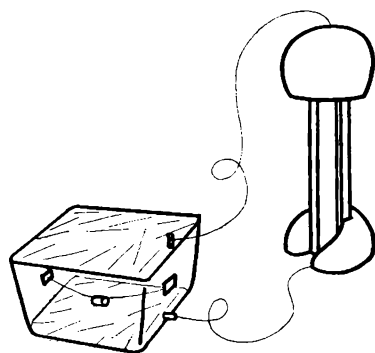


Fig. 10

- (i) Throw into the box a dozen pieces of drinking straw, each a little shorter than the height of the box. Switch on the Van de Graaff and see how the straws arrange themselves. Can you explain the arrangement?
- (ii) Replace the straws with a small polystyrene ball. Its surface should be conducting. How does it move when a p.d. is applied to the plates? Why?
- (iii) Make a small cylindrical tube of aluminium foil from a cigarette packet (about 1 cm long and 0.5 cm in diameter) and suspend it from a fine nylon thread stretched across the box as shown in Fig. 10. The length of the thread should

be such that the cylinder can touch the lower plate but *not* the top plate.

By slowly turning the Van de Graaff belt the cylinder can be balanced in the middle of the box. Reversing the direction of the belt reverses the p.d. When the cylinder is balanced what forces are acting on it?

Alternatively, the apparatus_{N142} in Fig. 11 may be used to investigate the force on a charged sphere suspended between two parallel plates between which there is a high potential difference.

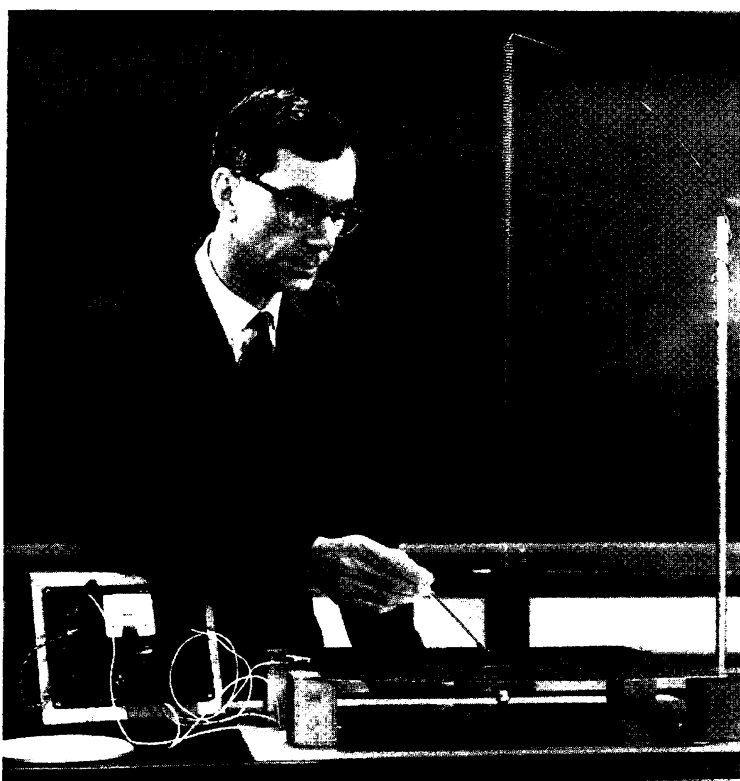


Fig. 11. From the Esso film 'Electrostatics—A Modern Approach'

Demonstration 1.6. A small transparent plastic box₅ used for biological specimens is suitable for this model. Fix a brass plate in the bottom and replace the plastic lid with a similar brass plate (Fig. 12). A hole should be drilled in the top plate and a collar fitted to allow the box to be filled with liquid paraffin. (The apparatus is now available commercially₂.)

A few dozen grains of fine sand may then be introduced and their movements studied with the help of a 35 mm projector.

- (i) Apply a high voltage (about 5000 V) to the plates until the sand grains are moving freely in the cell. Switch off the supply. What happens? Do all the grains move in the same direction? Explain this. Do they all have the same speed? Is the speed of each approximately constant?

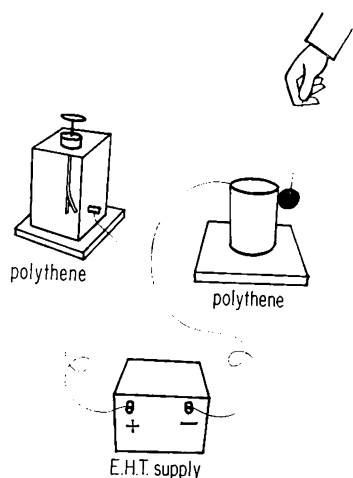


Fig. 32

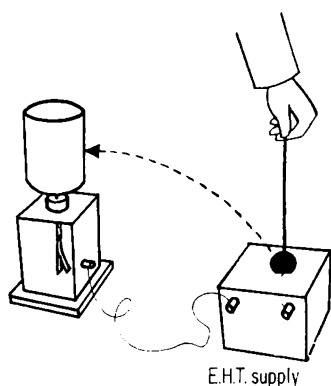


Fig. 33

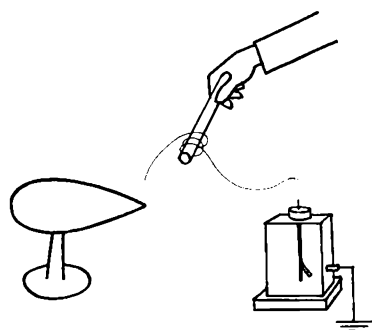


Fig. 34

greater charge? What does this tell you about the charge distribution when two charged bodies are in contact?

Problem 14. What happens to the charge on a charged conductor when it is earthed? Can you explain this in terms of the results of the last experiment?

Demonstration 2.8. Connect an electroscope and a can to an E.H.T. supply as shown in Fig. 32. The positive terminal of the E.H.T. supply should be earthed.

(i) Use a conducting sphere on a polythene handle, or an electrophorus plate, to transfer charge from the *outside* of the can to the plate of the electroscope. By repeating this several times can you charge the electroscope?

(ii) Repeat the above procedure, but now try to take charge from inside the can by allowing the sphere to touch only the bottom of the *inside* of the can. What do you find? What does this tell you?

Demonstration 2.9. Using the same apparatus as in Demonstration 2.8, place the can on the plate of the electroscope.

(i) Transfer charge from the negative terminal of the E.H.T. supply to the *outside* of the can using the sphere. Can you obtain a potential difference across the electroscope *greater* than the E.H.T. voltage?

(ii) Repeat the experiment, this time transferring the charge to the *inside* of the can. Can you produce a p.d. across the electroscope greater than the p.d. across the E.H.T. supply? Where has the extra energy come from? Can you see any similarity between this experiment and the Van de Graaff generator?

Problem 15. An electrophorus may be used to charge up a large hollow sphere by repeated applications of the charged plate to the *inside* of the sphere. Eventually the sphere will possess a fair amount of electrical potential energy. This energy could be used to do work. Where did it come from? (Hint: Provided the electrophorus plate is finally returned to its original position you can ignore gravity.)

Charge and Potential

Experiment 2.10

(a) Use a proof plane to investigate the charge distribution on the face and on the edge of a charged electrophorus plate. Transfer the charge from the proof plane to a can on top of an electroscope. Where is the charge density greatest?

(b) Alternatively, investigate the charge density on different parts of a charged can placed on a polythene slab.

(A pear-shaped conductor (Fig. 34) is also suitable but not essential for this experiment.)

Experiment 2.11

(i) With the same conductor as used in the previous experiment investigate the potential at various points on it. To do this connect a thin wire to an electroscope and let the other end touch various parts of the charged conductor (Fig. 34). Is the potential difference between the conductor and earth greatest where the charge density is greatest? Is there a p.d. across the conductor?

(ii) Use the same method to see if there is a potential difference between the inside and the outside of a charged can.

Now we have introduced another force, QV/d , and yet the forces are again balanced. *Can you explain this? (5)*

Since the mass can be found from the terminal velocity we can find the charge on the oil drop.

$$Q_1 = \frac{mgd}{V_1}$$

The charge on the oil drop can be altered by holding a radioactive source nearby or by sending a beam of X-rays between the plates. In either case the air is ionised, and when an ion collides

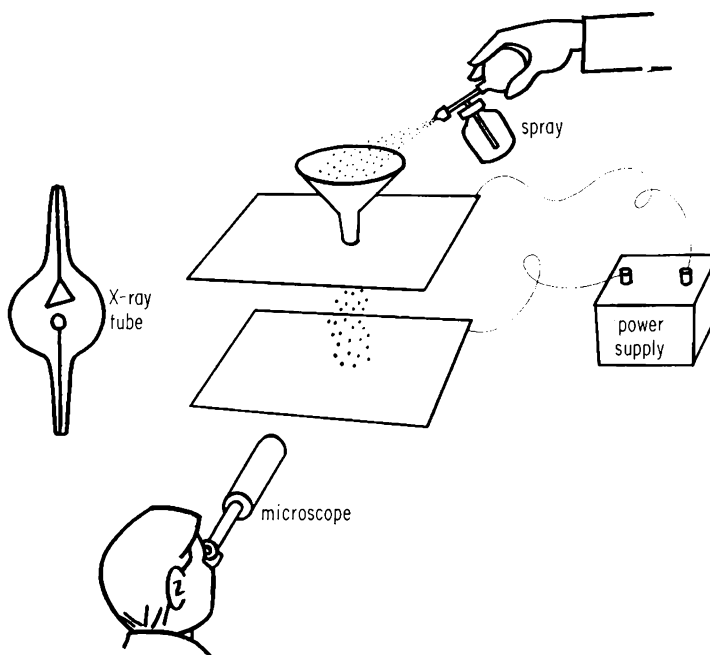


Fig. 14

with the oil drop the charge on the drop changes. The drop starts to move so that the p.d. across the plates has to be altered in order to stop it again. If the new p.d. is V_2 the new charge on the drop will be

$$Q_2 = \frac{mgd}{V_2}$$

This process is repeated several times to give Q_3 , Q_4 , Q_5 , etc., as the values of the charge on a particular drop.

Practical Puzzle 6. *To understand how Millikan's results can be interpreted, imagine that you are given twenty-one sealed bags which you are asked to weigh. The results in grammes are as follows.*

78.0	39.1	38.9	65.2	52.1	78.1	26.0
39.2	64.8	78.2	25.8	51.9	65.9	51.8
26.1	39.0	77.1	26.0	51.7	65.0	38.9

Record these results on a sheet of graph paper. Indicate the mass on the y axis, and mark each result with a cross at (say) 1 cm intervals

in the x direction. Can you discover anything about the contents of the bags? Were they more likely to be filled with marbles or marmalade?

From thousands of measurements Millikan discovered that the values of Q_1, Q_2, Q_3, Q_4 , etc., always produced the same kind of pattern. Can you find, from the following simplified results, what the pattern was? (7)

Charges on the oil drop ($\times 10^{-19}$ C).

6.4	4.8	12.8	14.4	3.2	8.0	12.8
9.6	8.0	16.0	4.8	11.2	6.4	12.8
3.2	4.8	6.4	8.0	12.8	3.2	9.6
8.0	3.2	9.6	6.4	16.0	11.2	12.8

From these results what seems to be the smallest unit of electric charge? (8) Why is it unlikely to be smaller? (9)

For his work on the measurement of the electronic charge Millikan received the Nobel prize for physics in 1923.

Problems

10. If the ratio of charge/mass for an electron is 1.76×10^{11} C/kg and the electronic charge is 1.6×10^{-19} C, what is the mass of the electron? Compare the mass of the electron with the mass of a hydrogen nucleus (proton), which is 1.67×10^{-27} kg. Was J. J. Thomson's hunch correct?

11. Using the value stated in the previous question, find the increase in the speed of an electron accelerated by a p.d. of 500 volts. (Hint: find the gain in the kinetic energy of the electron.)

12. If the electronic charge is 1.6×10^{-19} C, how many electrons are equivalent to a coulomb? How many of these charges pass a given point in a wire per second when a current of 1 ampere flows?

13. If a small sphere carries a negative charge of $0.1 \mu\text{C}$, how many excess electrons does it have?

14. In the electron deflection tube shown in Fig. 15, A represents the cathode, BC the anode and DE the deflecting plates, which are at the same potential as the anode. State where the electrons will be accelerating and where they will be travelling with a constant horizontal velocity.

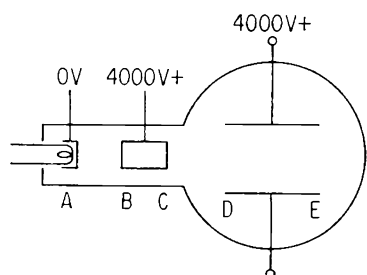


Fig. 15

Optional Extras

Electric Field Intensity ($\mathcal{E}$)

The gravitational field strength (g) near the Earth is the force (F) acting on each unit of mass (m) to produce acceleration.

$$g = \frac{F}{m}$$

newtons / kilogramme = newtons / kilogrammes

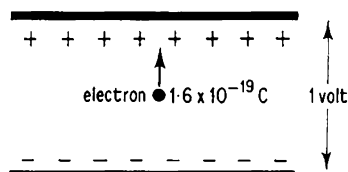


Fig. 17

If a charge of 1 coulomb is accelerated through a p.d. of 1 volt it gains 1 joule of kinetic energy. For some purposes a smaller unit is used. It is the energy gained by one electron (1.6×10^{-19} C) when accelerated through a p.d. of 1 volt (Fig. 17). This amount of energy is called the electron volt.

$$1 \text{ electron volt (eV)} = 1.6 \times 10^{-19} \text{ joules}$$

Problem 19. Find the energy, in electron volts, of an electron travelling at 10^6 m/s if the mass of the electron is 9.1×10^{-31} kg. Compare this with the average kinetic energy of an air molecule at room temperature which is 0.03 eV.

In particle physics it is often necessary to accelerate particles, for example electrons, to speeds much greater than those which can be achieved with even the highest voltages available (i.e. several millions of volts). An electron accelerated by a 10 million volt Van de Graaff generator would attain a kinetic energy of only 10^7 eV. Yet particle accelerators can produce thousands of millions of electron volts. How is this achieved?

The Linear Accelerator

The study of particles such as those which make up the atomic nucleus is one of the most important aspects of physics research today. To investigate subatomic particles, atomic nuclei are bombarded with high speed 'bullets', such as protons and electrons, fired from a particle accelerator. Linear accelerators, for example, are used to accelerate electrons to very high speeds approaching the speed of light.

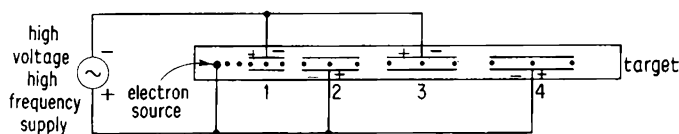


Fig. 18

In one type of accelerator a series of electrodes in the form of hollow sleeves are arranged inside an evacuated tube as shown in Fig. 18. *Why must the tube be evacuated?* (20) The sleeves are coupled to a high-frequency, high-potential source of energy. Electrons are fired from a source at one end of the tube and are accelerated towards a target at the other end. If an electron leaves the source when the sleeves are charged as shown in *red* the electron will be accelerated towards the first sleeve. Once inside it the electron will coast along at a steady speed as there is no field inside the sleeve. When the electron is inside sleeve No. 1 the voltages are reversed as shown in *black* so that the electron emerges to find sleeve No. 2 attracting it and sleeve No. 1 repelling it. The electron is therefore accelerated again. As the sleeve voltages are reversed during the time the electron is inside each sleeve, the electron is accelerated between the sleeves. So that reversals take place at the



Fig. 19

right time each sleeve must be longer than the previous one, the longest being nearest the target. A two mile long electron accelerator has recently been built in Stanford, U.S.A. (Fig. 19). With it electrons can be accelerated to 20 giga-electron-volts (1 GeV = 10^9 eV).

Electron Optics

A simple model of an electron lens system can be constructed from the Maltese cross tube. It can be used to magnify the shadow image of the cross.

Demonstration 1.7. Place a Maltese cross tube₁ (Tel 523) in the jaws of the stand with the Helmholtz coils round it as shown in Fig. 20. Watch what happens to the image when current is passed through the coils. Can you produce an *enlarged* image by varying the anode voltage and current through the coils?

Quarks

Millikan's experiment suggested that the electronic unit was the smallest possible quantity of electric charge. Some physicists now think that smaller charges may exist, although there is no experimental evidence to support this idea so far. The sub-electronic particles have been labelled *quarks*, and a full-scale quark-hunt is now in progress. Quarks carry one-third and two-thirds of an electronic charge, and one electronic charge might consist of two $-\frac{2}{3}e$ charges plus one $+\frac{1}{3}e$ charge. The quark may prove to be a fundamental elementary particle!

Summary of Chapter I

History

600 B.C. Rubbed amber attracts tiny fragments.

1833. Faraday's work on electrolysis could be explained in terms of charged particles.

1897. Discovery of the electron. J. J. Thomson found that cathode rays had charge (e) and mass (m) and was able to measure e/m .

1917. R. A. Millikan measured the charge on the electron (e) by measuring the *force* on a charged oil drop which could move freely between two horizontal plates.

Optional Extras

$$\text{Electric field intensity } (\mathcal{E}) = \frac{F}{Q}$$

$$\text{Potential gradient} = \frac{V}{d}$$

$$\frac{Q}{m} \text{ for hydrogen ion (proton)} = 9.58 \times 10^7 \text{ C/kg}$$

$$\frac{e}{m} \text{ for electron} = 1.76 \times 10^{11} \text{ C/kg}$$

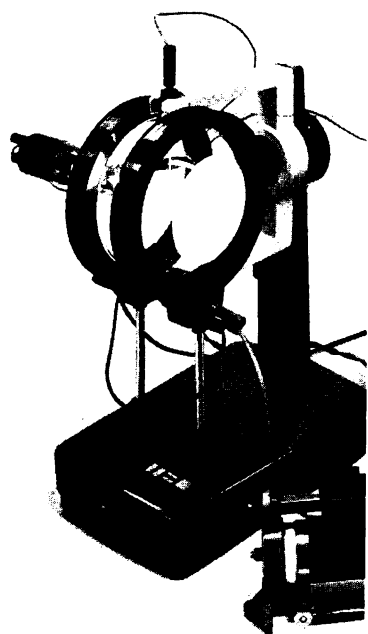


Fig. 20

Charge on electron (e)	$= 1.6 \times 10^{-19} \text{ C}$
i.e. 1 coulomb	$= 6.24 \times 10^{18} e$
Rest mass of electron (m)	$= 9.1 \times 10^{-31} \text{ kg}$
Rest mass of proton	$= 1.67 \times 10^{-27} \text{ kg}$
1 electron volt (eV)	$= 1.6 \times 10^{-19} \text{ J}$
i.e. 1 joule	$= 6.24 \times 10^{18} \text{ eV}$

Visual Aids

Filmstrips: The Electron₂₉ 08.0026.

Electrons at Rest

CHAPTER 2

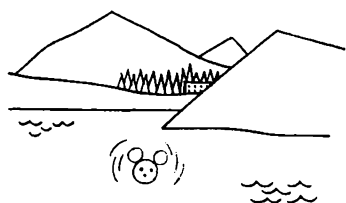


Fig. 21

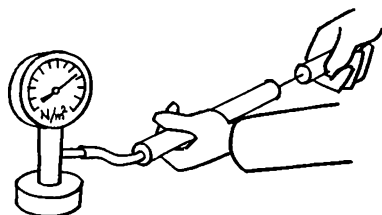


Fig. 22

A wee molecule on the surface of a highland loch might be shaking with excitement, yet we say that the water is *still*. We contrast this still water with the running water of a mountain stream. When we speak of *static* electricity we do not mean that the electrons themselves are stationary—they are forever vibrating, spinning and jumping—but simply that *on the average* they are going nowhere in particular. With static electricity there is no continuous flow of charge in any one direction.

In this chapter we continue the investigations begun in the second chapter of Book 2. You should therefore be sure that you can answer the questions asked there before going any further.

Measuring Instruments

If air is pumped into a Bourdon pressure gauge the pointer moves across the scale to indicate a higher pressure or—more accurately—a greater pressure difference (p.d.) between the air inside and outside the gauge. The more air molecules that are pumped in, the greater the pressure difference will be and the more difficult it will be to squeeze more molecules into the gauge. As the pressure difference increases, more work will have to be done to force each extra molecule into the gauge. The gauge reading (p.d.) will thus tell us something about the *work done per molecule*.

As the tube inside the gauge has a fixed volume (capacity), a higher reading of pressure difference will also indicate that there are more air molecules in the gauge itself. The gauge is not however designed to tell us how many air molecules there are in its flexible tube, but rather to indicate the pressure difference between the air in the apparatus to which it is attached and the atmospheric pressure. Atmospheric pressure is normally taken as a reference pressure.

The Electroscope

Experiment 2.1. Connect the plate of an electroscope to its case so that there can be no potential difference between them. Now place the electroscope on a polythene slab. Charge the electroscope with an electrophorus and see if the leaf is deflected. Does this suggest that the electroscope indicates charge or does it indicate potential difference?

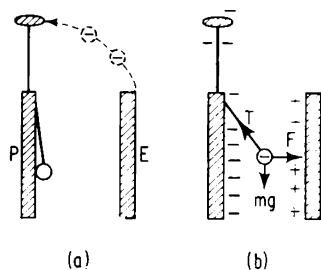


Fig. 23

Imagine two vertical parallel plates (Fig. 23 (a)). A light-weight conducting sphere is attached by a conducting thread to one plate (P). If electrons are transferred from E to P, the plate P and the sphere will become negatively charged and the sphere will be attracted to plate E (Fig. 23 (b)). The sphere will move towards E

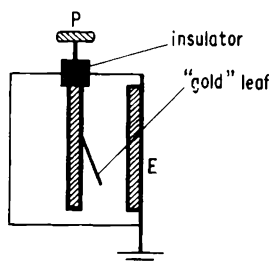


Fig. 24

until it is in equilibrium under the three forces; F , mg and T . From Demonstration 1.4 we know that the force F will increase as the p.d. between plates P and E increases; that is, the deflection of the sphere varies with the p.d. between the plates.

As more and more electrons are transferred from E to P there will be increasing opposition to the newcomers. More work will have to be done to move each extra electron off plate E and on to plate P. The work done per unit charge will increase; that is, the potential difference between P and E will increase. The deflection of the sphere can therefore be used as a measure of potential difference or *work done per unit charge*.

Our charged sphere between two parallel plates is a simple kind of electroscope. In practice a thin metal leaf (originally gold—now often Dutch metal) replaces the sphere, and the plate E is in the form of a conducting box which protects the delicate leaf. The box is usually earthed so that the deflection of the leaf indicates the p.d. between the plate P and earth E (Fig. 24).

When a scale is fitted to an electroscope, or the shadow is projected on a blackboard or screen so that it can be calibrated in volts, the instrument is often called an *electrometer*.

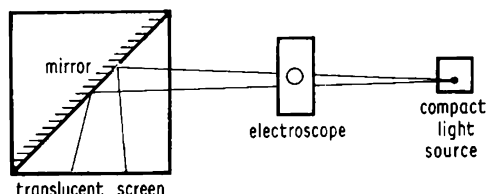


Fig. 25

Some electroscopes₄ fit neatly into an Aldis projector, which can be used to project a large shadow of the leaves on to a blackboard. Another form of shadow projection using a compact light source_{N21} is illustrated in Fig. 25. An old TV box can be used to house the mirror and translucent screen.

Demonstration 2.2. Connect an E.H.T. supply to a moving coil voltmeter and an electroscope as shown in Fig. 26. Does the deflection of the leaf vary with the applied voltage?

If the electroscope leaf is projected on to a blackboard, this arrangement can be used to calibrate the electroscope in volts.

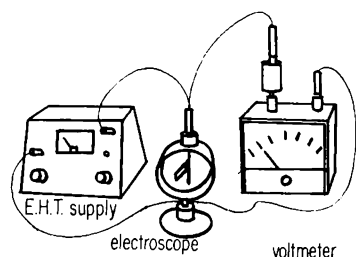


Fig. 26

Practical Puzzle 1. Can an electroscope be used to measure an alternating voltage? Explain why this is so. (Warning. Be very careful if you are using high voltages.)

Problem 2. When a bird sits on a very-high-voltage cable its feathers tend to spread out. Why? Does it receive an electric shock? Explain your answer.

Confusion

Having shown that an electroscope measures potential difference and *not* charge you are hardly likely to welcome the suggestion that we can also use an electroscope to indicate its own charge! Perhaps an analogy will help.

The Bourdon pressure gauge measures pressure difference but we also saw that it could be used to indicate the number of air molecules in the gauge itself. The pressure difference (p.d.) is proportional to the number of molecules (Q) in the gauge. We will see later that the potential difference across an electroscope is proportional to the quantity of charge (Q) on the plate and leaf when the case is earthed, so that we can use an electroscope in this way to tell us something about *its own charge*. We can say, for example, that when the leaves fall the electroscope is 'losing its charge'.

To sum up, then, we can say that the electroscope

- (i) measures the p.d. between the leaf and the case;
- (ii) indicates the charge (Q) on the plate and leaf when the case is earthed.

Profit and Loss

If the electron theory is correct, we would expect any object which has lost electrons to have a positive charge and an object gaining electrons to have a negative charge. It is unfortunate that the addition of these charged particles should be called a *negative* charge and the removal of these charges *positive*, but these labels were attached long before the electron was discovered. The charge on rubbed amber was originally called resinous or negative and the charge on glass was called vitreous or positive. A polythene strip rubbed with wool normally carries a negative charge, and a rubbed cellulose acetate strip carries a positive charge. In the following experiment you can investigate these charges.

Experiment 2.3.

- (i) Discharge a polythene rod by passing it very quickly through a bunsen flame. How can you test that it has been discharged?

Roll the polythene rod in a duster and push them into a can. Place the can on the plate of an electroscope (Fig. 27). Withdraw the polythene rod and watch the electroscope leaf. Test the polythene rod with another electroscope to see if it is charged.

Replace the polythene rod in the duster. What happens? What does this tell you?

- (ii) If it is a very dry day repeat this experiment with a cellulose acetate rod. Can the same duster now be charged negatively? Are electrons more easily removed from acetate or polythene?

Experiment 2.4. Discharge a polythene and an acetate rod. Test that they are discharged by inserting them one at a time inside a can placed on an uncharged electroscope.

Now rub the two rods together and see what happens when they are inserted (a) separately and (b) together in the can. What do the results suggest? How can you test the charges on the rods to see if they have the same polarity?

Practical Puzzle 3. Can a metal rod be charged by rubbing it with fur? Describe how you find out, and explain why you cannot use the same method as you did with the polythene rod?

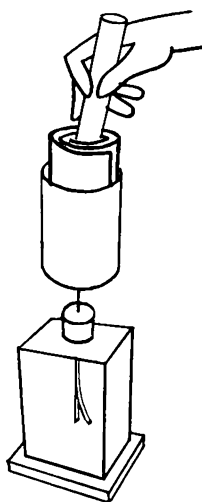


Fig. 27

Practical Puzzle 4. Can you charge the plate of an electroscope by rubbing it with a polythene rod or a piece of expanded polystyrene? Explain your results.

Like Charges Repel

We can assume that two identical polythene rods rubbed with similar dusters will each carry the same kind of charge. How would you demonstrate that two such rods repel each other? (5) How would you demonstrate that two unlike charges attract each other? (6) Is there a third kind of charge which will repel both charged polythene and charged acetate? (7) Will any kind of body attract both a charged polythene rod and a charged acetate rod? (8)

Experiment 2.5

(a) Test two conducting spheres, attached to polythene handles, to make sure that they are both uncharged. Bring the two spheres into contact close to a charged Van de Graaff dome as shown in Fig. 28. Now separate the spheres and test them with two electroscopes to see if they are charged? Are they? Have they the same kind of charge? If the dome is positively charged what charge will A carry? What kind of charge will B have? Can you explain this in terms of the movement of electrons?

Repeat this experiment, only this time touch the spheres together again after removing them some distance from the dome, but before testing their charges. Explain the result.

(b) Alternatively you can use a charged polythene rod instead of the Van de Graaff dome, and two cans standing on polythene blocks in place of the spheres.

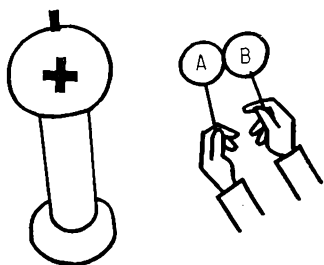


Fig. 28

Practical Puzzle 9. Draw a series of diagrams and use them to explain the action of an electrophorus. If a negatively charged polythene slab is used what charge does the metal plate carry?

Practical Puzzle 10. Explain how to charge an electroscope by induction using a negatively charged polythene rod (Book 2, page 19f). Is the electroscope positively or negatively charged? What happens to the leaves of a negatively charged electroscope when a positively charged object is brought close to the plate of the electroscope? What happens when a negatively charged object is brought close to the plate of such an electroscope?

If the leaves fall when an object is brought close to the plate of a positively charged electroscope, what does this tell you? (Hint: bring your hand close to the plate of such an electroscope.)

Practical Puzzle 11. The paper cover has been removed from a 120 volt battery so that you cannot tell which is the positive terminal. How could you use an electroscope to identify this terminal?

Problem 12. About 1730 Stephen Gray wanted to find out if the human body conducted electricity. He decided to suspend his servant from the ceiling by two lengths of strong silk cord. Gray then charged a glass rod and put it to the soles of the boy's feet. His nose then attracted small pieces of paper! Explain this in terms of the electron theory.



Fig. 29

Charge Distribution on a Conductor

In the following experiments you are asked to find out if electric charges are distributed evenly through a conductor—like cherries in a cake—or if they tend to congregate in certain places—like cherries in another cake!

Experiment 2.6

(i) When a deep can is placed on the plate of an electroscope and a charged sphere or electrophorus plate lowered into the can, the electroscope leaves diverge (Fig. 30). What happens when the sphere is removed? Is the sphere still charged? What happens if the sphere is allowed to touch the bottom of the inside of the can before being removed? Is the sphere still charged when removed?

The result of this experiment is sometimes stated thus:

$$\text{Induced charge} = \text{Inducing charge}$$

Can you explain, with reference to Fig. 30, what this means and why the result of this experiment justifies it?

(ii) Repeat the above experiment but allow the sphere to touch the outside instead of the inside of the can. Is the sphere still charged? Is the can charged?

(iii) A small conductor on an insulating handle is called a *proof plane*. By bringing a proof plane into contact with a charged conductor, some of the charge is transferred to the plane. Use a proof plane to test the charge on the inside and on the outside of a charged can.

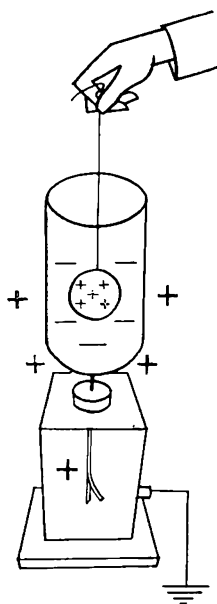


Fig. 30

Practical Puzzle 13. A charged sphere is lowered into a can placed on an electroscope. With the sphere in the position shown in Fig. 30 the can is earthed temporarily. What will happen to the leaf? The sphere is removed. Will the can be charged? If so will the leaf be deflected less, more or to the same extent as the leaf shown in Fig. 30?

The Selfish Conductor

When a charged conductor comes in contact with an uncharged conductor the former *shares* its charge with the other. There is one important exception—the selfish conductor. You can easily recognise him; he has his mouth wide open! He gives nothing away and any charges that enter and make contact with his throat never come out. Because of his enormous appetite for charges, this hollow conductor, has, however, many useful functions. The following experiments illustrate some of them.

Experiment 2.7. For this experiment you will need a small and a large conducting sphere, each on a polythene handle. Charge the larger sphere with an electrophorus and then bring the two spheres into contact so that the charge is shared (Fig. 31). Lower the small sphere into a deep can on an uncharged electroscope, allowing it to touch the inside of the can so that all its charge is transferred. Note the deflection.

Remove the small sphere, discharge the electroscope and insert the larger sphere in the can. Note the deflection of the leaf. Did both spheres carry the same charge? If not, which sphere had the

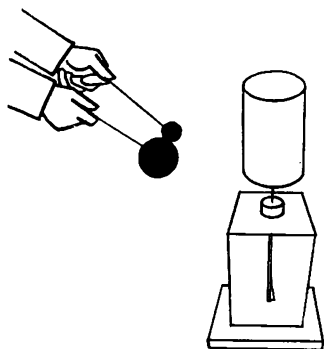


Fig. 31

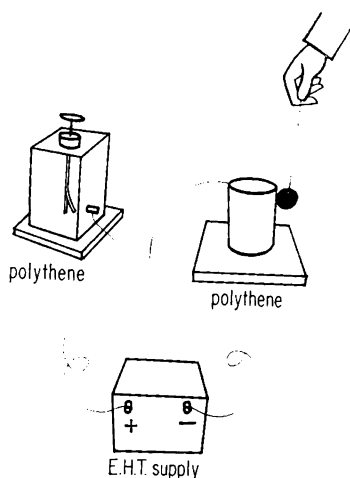


Fig. 32

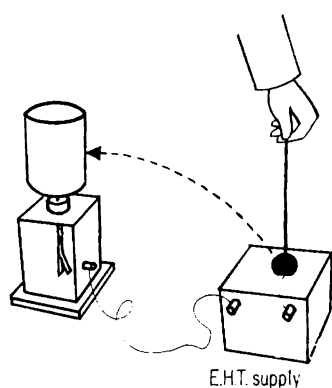


Fig. 33

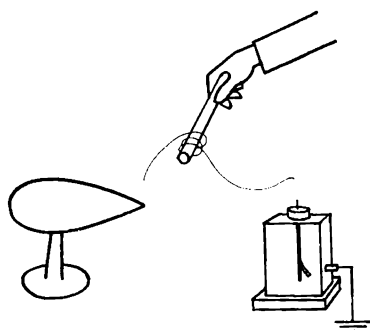


Fig. 34

greater charge? What does this tell you about the charge distribution when two charged bodies are in contact?

Problem 14. What happens to the charge on a charged conductor when it is earthed? Can you explain this in terms of the results of the last experiment?

Demonstration 2.8. Connect an electroscope and a can to an E.H.T. supply as shown in Fig. 32. The positive terminal of the E.H.T. supply should be earthed.

(i) Use a conducting sphere on a polythene handle, or an electrophorus plate, to transfer charge from the *outside* of the can to the plate of the electroscope. By repeating this several times can you charge the electroscope?

(ii) Repeat the above procedure, but now try to take charge inside the can by allowing the sphere to touch only the bottom of the *inside* of the can. What do you find? What does this tell you?

Demonstration 2.9. Using the same apparatus as in Demonstration 2.8, place the can on the plate of the electroscope.

(i) Transfer charge from the negative terminal of the E.H.T. supply to the *outside* of the can using the sphere. Can you obtain a potential difference across the electroscope *greater* than the E.H.T. voltage?

(ii) Repeat the experiment, this time transferring the charge to the *inside* of the can. Can you produce a p.d. across the electroscope greater than the p.d. across the E.H.T. supply? Where does the extra energy come from? Can you see any similarity between this experiment and the Van de Graaff generator?

Problem 15. An electrophorus may be used to charge up a hollow sphere by repeated applications of the charged plate to the *inside* of the sphere. Eventually the sphere will possess a fair amount of electrical potential energy. This energy could be used to do work. Where did it come from? (Hint: Provided the electrophorus plate is finally returned to its original position you can ignore gravity.)

Charge and Potential

Experiment 2.10

(a) Use a proof plane to investigate the charge distribution on the face and on the edge of a charged electrophorus plate. Transfer the charge from the proof plane to a can on top of an electroscope. Where is the charge density greatest?

(b) Alternatively, investigate the charge density on different parts of a charged can placed on a polythene slab.

(A pear-shaped conductor (Fig. 34) is also suitable but essential for this experiment.)

Experiment 2.11

(i) With the same conductor as used in the previous experiment investigate the potential at various points on it. To do this connect a thin wire to an electroscope and let the other end touch various parts of the charged conductor (Fig. 34). Is the potential difference between the conductor and earth greatest where the charge density is greatest? Is there a p.d. across the conductor?

(ii) Use the same method to see if there is a potential difference between the inside and the outside of a charged can.

Ionisation at Sharp Points

As the charge density is very great at a sharp point there is a very strong electric field near it. In air there are always a few electrons present which can be accelerated by the field to such a speed that when they collide with air molecules other electrons are knocked out and positive ions are produced. The released electrons continue the ionising process. Lightning conductors depend on this ionisation produced at sharp points (see Book 2, page 28).

A spark from a surgeon's scalpel could be extremely dangerous in the presence of inflammable gas. To prevent his being electrically charged by friction if he shuffles along the floor in his rubber boots, they and the linoleum are made conducting by the inclusion of carbon.

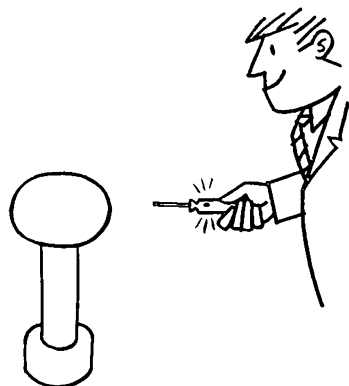


Fig. 35

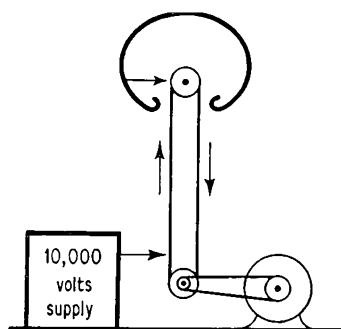


Fig. 36

Practical Puzzle 16. Attach a needle with Sellotape to the back of an electrophorus plate. Explain how this could be used to charge an electroscope without touching the plate of the electroscope. If the electrophorus was positively charged what charge would the electroscope receive?

Practical Puzzle 17. You are given two electroscopes, a needle and a negatively charged polythene rod. How could you put a negative charge on one electroscope and a positive charge on the other electroscope? Explain the action in each case.

Practical Puzzle 18. Some screwdrivers contain a neon bulb. They are used to test which mains wire is 'live'. Hold such a screwdriver near a charged Van de Graaff dome and explain why it lights up (Fig. 35).

Problem 19. Why is it important that blobs of solder used on very high voltage equipment should be spherical?

Problem 20. Fig. 36 illustrates a simple Van de Graaff generator. Explain its operation in terms of (a) sharp points and (b) a hollow conductor.

In the smaller Van de Graaff generators used in schools there is no high voltage supply. The rubber belt is charged by contact with the lower roller.

Problem 21. A large metal aircraft hanger contains a huge Van de Graaff generator. Where would be the safest place in the hanger for you to stand when the dome was fully charged?

Problem 22. Explain why sliding out of a P.V.C. covered car seat or removing nylon clothing can produce sparks and shocks!

Storing Electrical Energy

During the early part of the 18th century there were many attempts to construct machines which would produce large electric charges. Hauksbee used a rotating glass sphere which he rubbed with a woollen cloth, and later von Guericke constructed a similar machine with a sulphur ball. One obstacle to producing a large charge was the absence of any device for storing charge. Various attempts had been made without success, and then in 1745 a suitable device was discovered by scientists in Germany and in Holland.

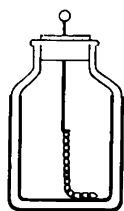


Fig. 38

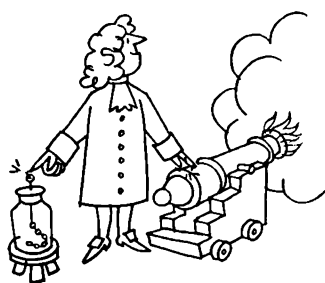


Fig. 39



Fig. 40

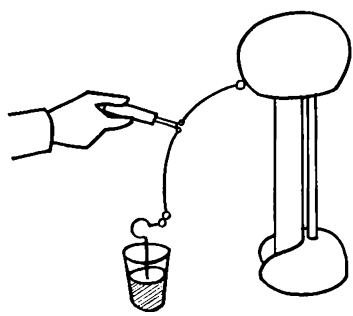


Fig. 41

In one experiment a bottle of water was used to see if it would hold electric charges. An electric machine consisting of a rotating sphere produced the electric charges, which were conducted away by a metal bar suspended on silk threads. The water-filled bottle was fitted with a cork, and a nail through the cork led the charge into the water. The Abbé Nollet was one of the first men to hold

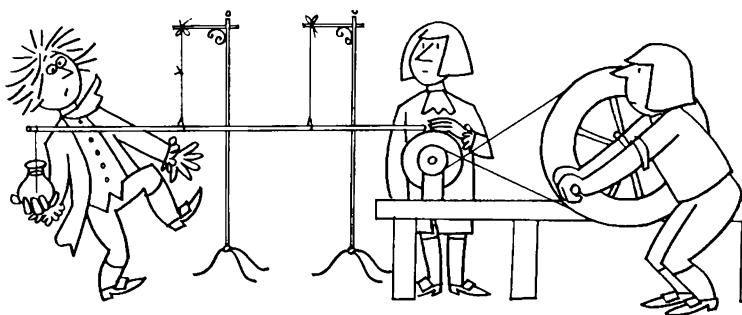


Fig. 37

such a bottle to the end of the conducting bar (Fig. 37). He received an unexpected and substantial shock! Later experiments showed that the charge was not stored in the water. The accumulation of charge seemed to depend on the glass between the water and the Abbé's hand. Soon, glass bottles were being coated inside and outside with metal foil and even greater shocks produced. These were called Leyden jars (Fig. 38) after the Dutch town in which they were developed.

The Leyden jar was regarded by many as an interesting gimmick rather than an important scientific discovery. Such tricks as firing a cannon (Fig. 39) or shocking a few hundred monks at one time (Fig. 40) were more fun than puzzling over the storing of electrical energy!

It was later discovered that even the glass could be dispensed with provided some other means could be found of keeping the two metal foils apart. The device formed is called a *capacitor*. When a capacitor is charged, the two plates (foils) carry equal and opposite charges. When we speak of the 'charge on a capacitor' we are referring to the size of the charge on *either* plate.

Demonstration 2.12. Charge a demountable Leyden jar₄ with a Van de Graaff generator (Fig. 41). Dismantle the jar and touch the metal cups together so that they are no longer charged. Now reassemble the jar and produce a spark! Where was the energy stored?

Warning: capacitors can give nasty shocks; always handle them with care.

Project 2.13. You might like to construct a model which illustrates the principles used in one of these early experiments. An old gramophone disc may be used in place of the sulphur sphere and a woollen cloth used as the rubber. The charge can be taken from the disc by a metal comb and carried to a capacitor made from a polythene cup coated with aluminium foil inside and outside. If a

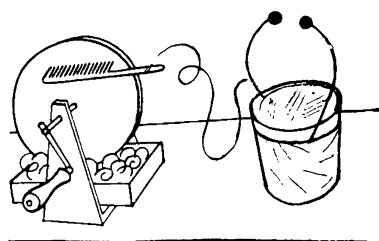


Fig. 42

small sphere is connected to each foil a spark can be produced. For dry air a potential difference of approximately 30,000 volts is needed to produce a spark 1 cm long.

Storage Capacity

If you were given a tractor tyre and a bicycle tyre you would have little difficulty in saying which had the greater capacity. Suppose, however, that the tyres were concealed behind a screen and only the valves—which we will assume to be identical—protruded. *How could you use a foot pump and a pressure gauge to identify the bigger tyre? (23) If one tyre takes 10 strokes of the pump to reach a certain pressure and the other 400 strokes to reach the same pressure, which has the greater capacity? (24)*

Charge (Q) and P.D. (V)

In the next experiment you can use an electroscope to investigate the change in potential difference between the plates of a capacitor when different quantities of charge are transferred from one plate to the other.

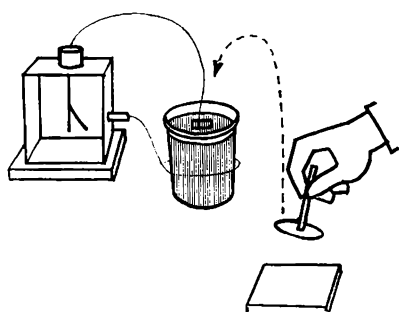


Fig. 43

Experiment 2.14. Construct two Leyden jar capacitors from polythene tumblers and aluminium foil. Glue the foil on to one tumbler so that the inside and outside surfaces are covered except for a 1-centimetre gap round the rim of the tumbler. Cover only half the inner and outer surfaces of the second tumbler with the aluminium foil.

Connect the inner foil of the first capacitor to the leaf of an electroscope and join the outer foil to the case of the electroscope (Fig. 43). The second (earth) wire is not required if the capacitor and the electroscope are standing on a reasonably good conductor such as wood.

(i) Charge an electrophorus by touching it momentarily when it is lying on a charged polythene plate. In this way electrons are forced through you to earth and so to the outer plate of the capacitor which is earthed through the bench. The positive charge on the electrophorus should then be transferred to the inner plate of the capacitor. How can you ensure that *all* the charge is transferred? Count the number of 'strokes' required to produce (say) a 50° deflection of the electroscope leaf.

(ii) Repeat this experiment with the half-coated capacitor, and see if more or less charge is required to produce the same p.d. between its plates, that is, the same deflection of the leaf. Which capacitor requires more charge to produce the same p.d.? Which capacitor has the greater capacitance?

Demonstration 2.15

(i) Connect the fully coated Leyden jar capacitor to a calibrated electroscope (Demonstration 2.2), and use a charged electrophorus to transfer charge as in the last experiment. Assume that the charge transferred is the same for each stroke, so that you can investigate the change of p.d. between the plates (V) with the charge transferred (Q) (Fig. 44). Record your results.

Charge Q (strokes)	p.d. V (volts)	$\frac{Q}{V}$

Complete the last column in the above table and describe how the p.d. varies with charge. Plot a graph showing how V varies with Q .

(ii) Repeat this experiment with the smaller capacitor.

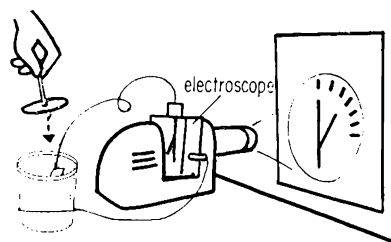
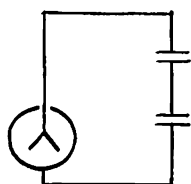


Fig. 44

The Farad

From the results of the last experiment we see that for a given capacitor the ratio Q/V is constant. We use this ratio as a measure of capacitance. If one coulomb of charge is needed to change the p.d. between the plates by 1 volt, the capacitance is 1 farad.



$$\frac{\text{coulombs}}{\text{volts}} = C \text{ farads}$$

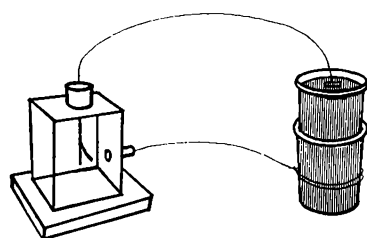


Fig. 45

Experiment 2.16

(i) Connect a fully coated Leyden jar to an electroscope, as in the last experiment, and count the number of charging strokes needed to produce a deflection of (say) 50° .

(ii) Now stack two uncharged Leyden jars so that the capacitors are in series as shown in Fig. 45. Connect the outer case of the lower jar to the earth terminal of the electroscope, and charge the inner foil of the upper jar as before. How many strokes are now needed to obtain the same p.d. (50° deflection) as before? Has the capacitance halved or doubled?

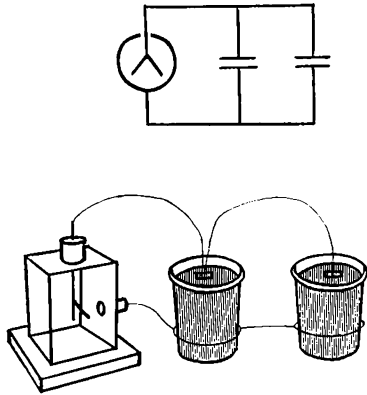


Fig. 46

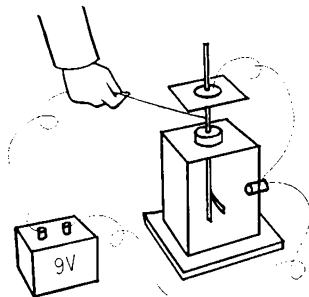


Fig. 47

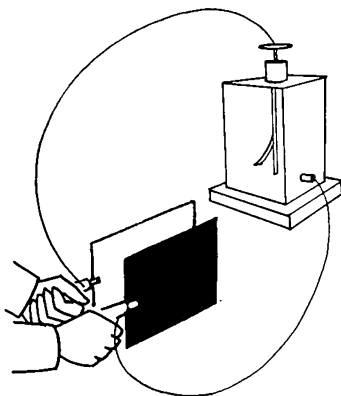


Fig. 48

(iii) Now stack three uncharged Leyden jars in series and find the charge needed to obtain the same p.d. How does the capacitance compare with the capacitance of one jar?

(iv) Connect two uncharged Leyden jars in parallel as shown in Fig. 46. If one is then charged, will the other be charged at the same time? Find the charge needed to obtain a 50° deflection of the leaf. Does your result suggest that the capacitance of two Leyden jars in parallel is half or twice the capacitance of one jar?

(v) Repeat the above experiment with three capacitors in parallel.

Problem 25. A $100\ \mu\text{F}$ ($10^{-4}\ \text{F}$) capacitor is charged to 50 volts. How much charge has been transferred from one plate to the other? If it were discharged completely in 2 milliseconds what would be the average current?

Problem 26. An electroscope has a capacitance of 10^{-10} farads. What charge will it hold if it is charged to 1200 volts?

Practical Puzzle 27. A thin uncharged polythene sheet lies on the plate of an electroscope. An electrophorus plate is then placed on top of it and connected by a wire to the electroscope case. One terminal of a 9 volt battery is also taken to the case of the electroscope and a wire from the other terminal is touched momentarily on to the electroscope plate (Fig. 47). What happens when the electrophorus plate is raised? Why? Has the system gained energy, other than gravitational potential energy when the plate is raised? If so, where has it come from?

Problem 28. Why do the leaves of an electroscope fall slightly if you bring your hand near the plate?

The Parallel Plate Capacitor

For most practical purposes capacitors consist of two metal plates separated by an insulator of some kind. They are used in all radio and TV sets and in computers and electronic flash guns. Capacitors are also used as suppressors on electric motors and in car engines.

Using the relationship $Q = VC$, you can investigate the factors affecting the capacitance of a parallel plate capacitor.

Experiment 2.17. A simple capacitor can be constructed from two pieces of hardboard, each attached to a strip of polythene to act as a handle. Glue a sheet of aluminium foil on one side of each piece of hardboard and connect a wire to it. Connect one sheet to the case of an electroscope and the other to the electroscope plate (Fig. 48). Hold the two plates a few centimetres apart and charge them until the electroscope leaf is deflected to an angle of about 45° .

(i) Keep the plates the same distance apart but slide them away from each other, thus reducing the area of overlap. What happens to the p.d.? What has happened to the capacitance?

(ii) Return to the original position and then pull the plates apart. What happens to the p.d. and to the capacitance? Move the plates closer together. What happens?

(iii) Finally, fix the plates parallel to each other and sufficiently far apart to allow you to slide slabs of paraffin wax, polythene or perspex between them without touching the plates. Such insulating

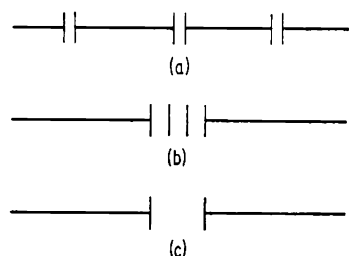


Fig. 49

materials are called *dielectrics*. Charge the plates and see if their capacitance is affected by introducing insulating slabs between them.

Complete the following statements.

Capacitance increases when the area of overlap . . .

Capacitance increases when the plates are moved . . .

Capacitance . . . when a dielectric is introduced.

Problem 29. Fig. 49 (a) shows three capacitors in series. Fig. 49 (b) shows them pushed close together so that their inside plates coincide. Fig. 49 (c) shows the two central plates removed. If the central plates are thin, Fig. 49 (c) is equivalent to Fig. 49 (a). Do you think the total capacitance of three capacitors in series is greater or less than that of each capacitor?

Problem 30. Fig. 50 (a) shows three capacitors in parallel. Fig. 50 (b) shows them pushed together, and Fig. 50 (c) shows them so close that the plates touch. Fig. 50 (c) is equivalent to Fig. 50 (a). Do you think the total capacitance of three capacitors in parallel is greater or less than that of each?

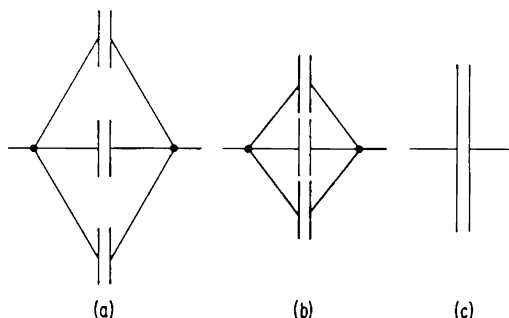


Fig. 50

The Dielectric

We have seen from the last experiment that the capacitance of two parallel plates depends on the material between the plates. When a dielectric is introduced, the plates can hold more charge for every volt of potential difference across them; that is, the capacitance (coulombs per volt) is increased. There is no flow of charge in the dielectric, which is an insulator, but the molecules are either re-aligned (polar molecules) or their charge distribution is re-arranged (non-polar molecules) as shown in Fig. 51 (b). The positively charged nuclei of the atoms can be displaced slightly towards the negative plate and the negatively charged electrons can be shifted slightly towards the positive plate. Energy is required to do this, and the capacitor stores this energy in the form of dielectric strain. This explains the result obtained in Demonstration 2.12 (page 24).

If the insertion of a slab of dielectric material doubles the capacitance of two plates previously separated by air, the dielectric material is said to have a *dielectric constant* of two. If it trebles the capacitance its dielectric constant is three, and so on.

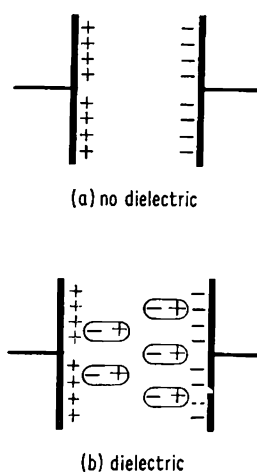


Fig. 51

Here are some approximate values for common dielectrics.

Material	Dielectric constant
Air	1
Waxed paper	2
Mica	7
Ceramics	6-4000

Many of the capacitors in radio, television and other electronic equipment use these dielectrics. Fig. 52 shows some of them. As the farad is too large a unit for most purposes, we use microfarads ($1 \mu\text{F} = 10^{-6} \text{ F}$) and picofarads ($1 \text{ pF} = 10^{-12} \text{ F}$).

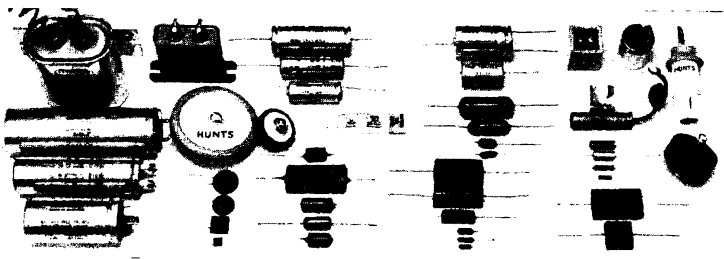


Fig. 52

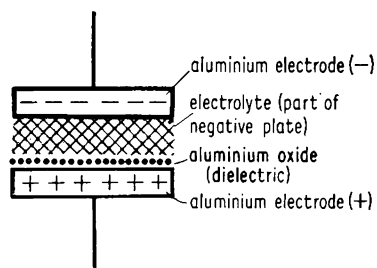


Fig. 53

The largest capacitors in commercial use are *electrolytic capacitors* (Fig. 53). The dielectric is a very thin film of aluminium oxide formed on the *positive* aluminium plate. The negative plate consists of an electrolyte and another aluminium plate. Such capacitors must not be charged in the reverse direction as the oxide layer will decompose. Electrolytic capacitors can have capacitances of several thousand microfarads.

Problem 31. A parallel plate capacitor has air as its dielectric. How would its capacitance be altered if

- a thin metal sheet were held by an insulator mid-way between the capacitor plates?
- a thick metal block were held by an insulator between, but not touching, the capacitor plates?
- a block of paraffin wax were inserted between the plates?

Practical Puzzle 32. In a radio tuning capacitor air is often used as the dielectric (Fig. 54). A tuning capacitor with its vanes closed is connected to an electroscope and charged. What will happen to the deflection of the electroscope leaf when the capacitor's vanes are opened? Explain the answer you give.

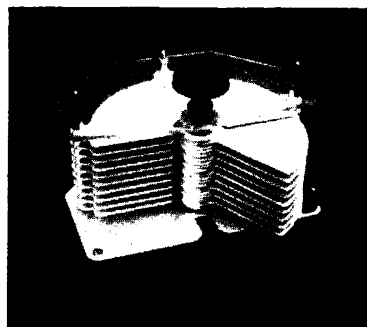


Fig. 54

Charging Currents

If we use an electrolytic capacitor of several thousand microfarads, we can study both the charging current and the p.d. across it with an ordinary moving coil meter.

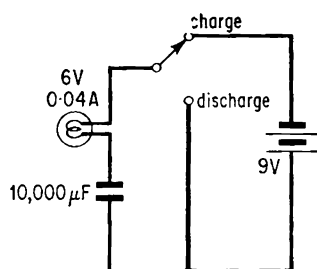


Fig. 55

Demonstration 2.18

(i) Using the circuit shown in Fig. 55, switch to the 'charge' position. What happens? Does charge flow through the capacitor₁₄? Now switch to the 'discharge' position. Explain what you see.

(ii) Switch to the 'charge' position and, when the bulb goes out, disconnect the battery, leaving the switch at 'charge'. Reconnect the battery. Does the bulb glow? Explain why this is so.

When a capacitor is connected as shown in Fig. 56 (a), no electrons flow and there is no p.d. across the plates of the capacitor. When the switch is closed as in Fig. 56 (b), electrons flow in the direction shown and the capacitor is charged. When the p.d. across the plates is equal to the p.d. of the cell, the current stops (Fig. 56 (c)). *What would happen if the switch were now opened? (33) Can energy be stored in a capacitor? (34)*

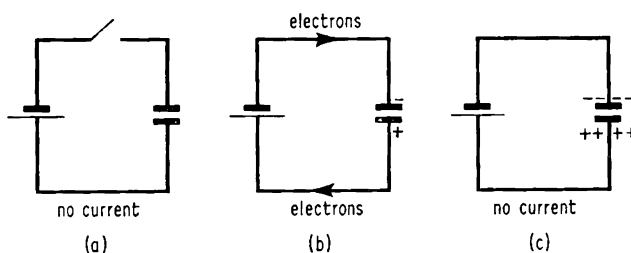


Fig. 56

Problem 35. How does the water-filled model in Fig. 57 resemble the circuit in Fig. 56?

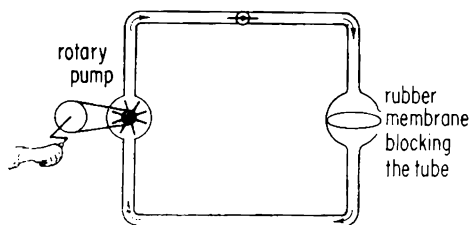


Fig. 57

Experiment 2.19. Charge a $10,000 \mu\text{F}$ capacitor with a 9 volt battery. Disconnect the capacitor from the battery and then discharge it through (a) a torch bulb, and (b) a small 3 volt electric motor. Describe the energy changes that take place in each case.

Demonstration 2.20

(a) Use a very high resistance voltmeter in the circuit shown in Fig. 58 (a). Close the switch and observe the meter readings carefully. Which meter reads first? Why does the voltmeter not read 9 volts immediately? Draw rough graphs showing the current change with time and the p.d. variation with time. What happens

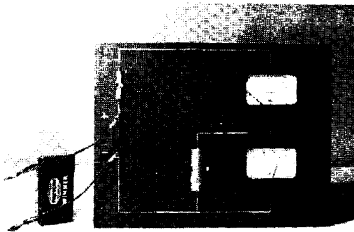
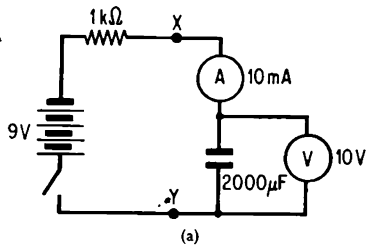
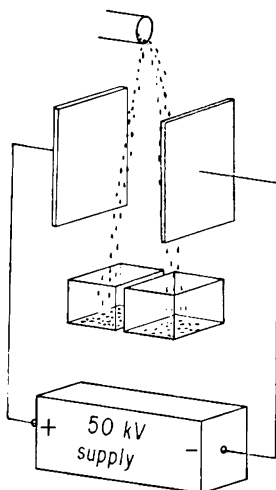


Fig. 58



when the switch is opened? Why does the voltmeter reading not immediately return to zero?

(b) If a very high resistance voltmeter is not available, connect a moving coil voltmeter across XY so that the milliammeter does not read the voltmeter current. Explain the reverse current in the milliammeter when the switch is opened.

Electrostatic Engineering

The importance of electrostatic equipment in industry is increasing rapidly at the present time. To cope with the demand for high-voltage d.c. supplies, many new electrostatic generators are being designed, some capable of working at several kilowatts. Van de Graaff machines are still used to produce the highest voltages—up to 10 million volts—but for many industrial applications much smaller voltages are sufficient.

One important application of electrostatics is the precipitation of fly-ash in chimneys. A large power station can produce many tons of fly-ash every hour so that a precipitator is essential (Book 2, page 19). Electrostatic paint spraying and crop spraying are similar in principle.

Electrostatics can be used to separate the components of a mixture; tea leaves can be sorted from unwanted fragments and seeds of one kind separated from another. Two types of crystal which become charged with opposite signs as they rub together can be separated by pouring them between two charged plates (Fig. 59).

New techniques have been developed for high-speed printing with electric charges. As the type and paper do not need to come into contact it is possible to print on almost any kind of surface. The photograph at the foot of this page shows some electrostatic printing on a raw egg! Another form of electrostatic printing—Xerography—is widely used in office copiers.

Optional Extras

From the relationship $Q = VC$, we see that the charge (Q) on a capacitor is directly proportional to the capacitance (C) when the voltage across it is constant. If, then, we *increase* the capacitance of a variable capacitor, keeping the voltage across the plates constant, the charge on the plates must increase. *How could you tell if the charge had increased or decreased?* (36)

If now, with the voltage still constant, the capacitance is decreased, what will happen? (37) The following demonstrations should enable you to check your answers to these questions.

Demonstration 2.21. A large tuning capacitor with good insulation and fairly wide air gaps between the vanes is needed for this experiment. Capacitors from high frequency transmitters are suitable.

Place a galvoamplifier₉ on polythene blocks and wire it to the variable capacitor and an E.H.T. supply fitted with a voltmeter or

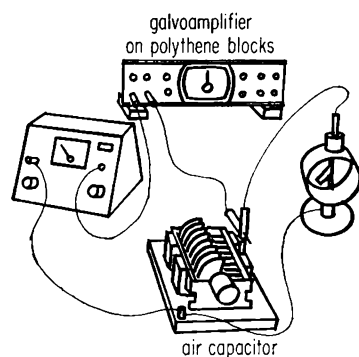


Fig. 60

bleeder across the output terminals. Connect an electrostatic voltmeter across the capacitor to act as a voltmeter (Fig. 60).

(i) Set the capacitor vanes half open and the E.H.T. supply to give approximately 1 kV. Switch on the E.H.T. and note the direction of the charging current. What happens when the power unit is switched off?

(ii) Switch on the E.H.T. again and note the deflection of the leaves. Does the deflection vary if the capacitance is now increased by closing or decreased by opening the vanes? What does this tell you about the p.d. across the capacitor?

(iii) What did you see happening as the capacitance was being increased? Can you explain this? What happens when the capacitance is decreased? Why?

(iv) Again set the vanes half open, charge up the capacitor and disconnect the power supply. If now the capacitance is increased or decreased will the charge vary? Explain your answer.

What happens when the vanes are being closed? What does this tell you? Explain.

How does opening the vanes affect the electrostatic voltmeter leaf? What has now happened to (a) the capacitance, (b) the charge, (c) the p.d. across the capacitor? Is this what you would expect from the relationship $VC = Q$?

Ballistic Galvanometer

An electric current (I) can be measured by measuring the force acting on a current-carrying conductor. A simple current-balance was illustrated in Book 2, p. 153. The unit of current (the ampere) is defined in terms of the force acting on a conductor, although the balance used is rather more refined! (Fig. 61). The unit of electric charge (the coulomb) is then defined as the charge which crosses any section of a conductor when 1 ampere flows for one second.

$$Q = It$$

coulombs amperes seconds

If a charged conductor, for example the sphere of a Van de Graaff generator, is discharged in a small fraction of a second we can use a sensitive microammeter to indicate the total charge on the conductor. The charge (Q) is proportional to the deflection of the spot of light. One coulomb is equivalent to 6.24×10^{18} electronic charges.

Demonstration 2.22. Charge a Van de Graaff sphere, switch off the motor and allow the sphere to discharge through a mirror galvanometer.^{6.27}

Repeat the experiment with two spheres of very different sizes, each charged to the same potential. How would you ensure that they were at the same potential with respect to earth? Do they both carry the same charge?

Summary of Chapter 2

An electroscope measures p.d., which is work done/unit charge.

Charging

1. Insulators and conductors may be charged by contact (rubbing).
2. Conductors may be charged by (a) induction, and (b) sharing.

Charged Conductors

1. Excess charges lie on the *surface* of a conductor.
2. There is no charge on the *inner* surface of a hollow conductor.

Capacitors

1. Electric charge can be stored in a capacitor $Q = VC$.
2. Capacitance increases with area of overlap of plates.
3. Capacitance decreases as plates move further apart.
4. Capacitance depends on dielectric between plates.

Visual Aids

Filmstrips: Static and Current Electricity₃₀ 5150.

Principles of Electrostatics₃₅ E113.

16 mm Films: Electrostatics₂₉ 21.7470.

Electrostatic Charge₃₁ DC.2791.

Electrostatics—A Modern Approach₃₇ (for teachers)

Electrons in Motion $\rightleftharpoons$ Heat

CHAPTER 3

International Quartet

Our study of the flow of electric charges in metallic conductors began in Book 2, Chapter 10. We will extend our investigations by using four important electrical units named after four famous scientists; the French physicist André Marie Ampère, the Italian physicist Count Alessandro Volta, the German physicist Georg Simon Ohm and the Scots engineer James Watt. The unit of electric current, the *ampere*, is named after the first, the unit of potential difference, the *volt*, after the second, the *ohm* is the unit of resistance and the *watt* the unit of power.

There have been in the past many ways of defining electrical units, but in this course we will consider only the present-day definitions used in the international system (SI). The electrical units are now based on the metre (length), the kilogramme (mass), the second (time) and the ampere (current). The metre is defined in terms of a particular wavelength of light; the kilogramme is defined as the mass of the international standard kept at Sèvres, near Paris; the second is based on a natural frequency of the caesium atom and the ampere is defined in terms of the force per metre between two long parallel wires.

From these four units—m, kg, s, A—the other units are derived as follows.

newton: unit of force
mass $\times$ acceleration

$$\text{kg} \times \frac{\text{m}}{\text{s}^2}$$

joule: unit of energy
force $\times$ distance

$$\text{kg} \cdot \frac{\text{m}}{\text{s}^2} \times \text{m}$$

coulomb: unit of electric charge
current $\times$ time
A $\times$ s

volt: unit of potential difference
energy per unit charge
joule/coulomb
 $\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} / \text{A} \cdot \text{s}$

ohm: unit of resistance
p.d. per unit current
 $\frac{\text{volt}}{\text{ampere}}$

$$\frac{\text{kg} \cdot \text{m}^2}{\text{A} \cdot \text{s}^3} / \text{A}$$

watt: unit of power
energy per second
 $\frac{\text{joule}}{\text{second}}$

$$\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2} / \text{s}$$

The Ampere

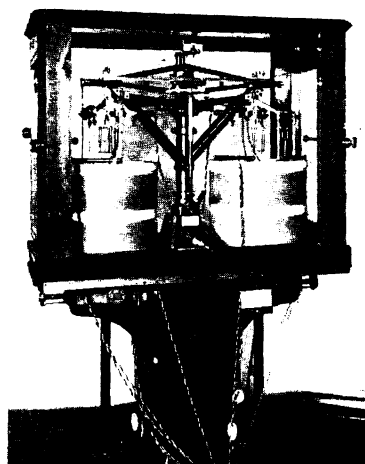


Fig. 61

André Marie Ampère (1775–1836) was perhaps the first person to realise that magnetism was directly related to the movement of electric charges. He found that, when two parallel wires carried currents in the same direction, the wires were attracted towards each other and, when the currents were in opposite directions, the wires repelled each other. (Book 2, page 133.) *How does this compare with the behaviour of like and unlike static charges?* (1)

Ampère also suggested that the magnetism of iron could be explained in terms of minute circulating currents, thus brilliantly anticipating modern theories of magnetism.

To *define* the ampere the force between two parallel current-carrying conductors is measured. If 1 ampere flows in two long wires 1 metre apart the force acting on each conductor is 2×10^{-7} newtons per metre. In practice coils of wire are used to measure this force (Fig. 61).

The coulomb is then defined by considering the charge moved by I amperes in t seconds. It is $I \times t$ coulombs.

$$\begin{array}{ccc} \text{coulombs} & = & \text{amperes} \times \text{seconds} \end{array}$$

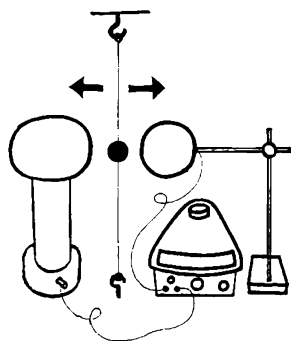


Fig. 62

Though it is *defined* in this way, it is perhaps easier to *think* of the coulomb as a basic unit (6.24×10^{18} electronic charges) and to regard 1 ampere as a flow of charge at the rate of 1 coulomb per second. With a current of 1 ampere, 6.24×10^{18} electronic charges pass a point in a conductor every second.

Demonstration 3.1. Connect one wire from a mirror galvanometer_{6.27} to a sphere placed about 10 cm from a Van de Graaff dome and the other wire to the base of the generator (Fig. 62). Paint a table tennis ball with Aquadag₇ and attach it to a thread which is held taut as shown. The ball should be able to vibrate between the two conductors so that it can carry charge from the dome to the sphere.

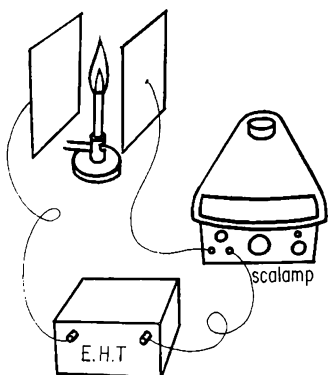


Fig. 63

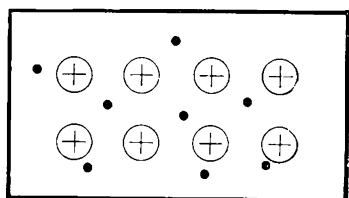


Fig. 64

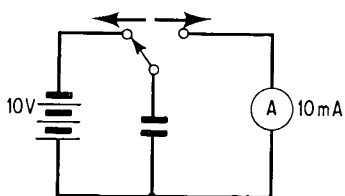


Fig. 65

(i) Switch on the Van de Graaff and allow the ball to vibrate. Note the current in the galvanometer.

(ii) Bring the sphere closer to the dome so that the rate of vibration increases. In this way the rate of flow of charge will be increased. How does this affect the current reading?

Demonstration 3.2. Connect a 5 kV E.H.T. supply via a mirror galvanometer to two parallel metal plates placed about 10 cm apart (Fig. 63). When the power unit is switched on is there a reading on the meter? What happens if a Bunsen burner is lit and placed between the plates? Can you explain this in terms of the movement of electric charges?

In liquids and gases both positively and negatively charged particles (ions) can move, but in metals, with which this chapter is mainly concerned, the flow of charge depends on the movements of free electrons. The flow of heat in a metal is also related to the movement of these electrons. The structure of a metal is illustrated in Fig. 64. It shows a regular arrangement of positive ions surrounded by a 'sea' of electrons. The ions remain more or less fixed in position, apart from a small amount of vibration which depends on the temperature of the metal. The electrons, on the other hand, are free to move in a random way at speeds of up to 10^6 m/s. If, however, an electric field is applied to the metal there is, superimposed on this random motion, a regular *drift* in one direction. This electron drift constitutes the current in a metal.

Problems

2. What constant current is required to transfer 300 coulombs in 1 minute?

3. If a current of 150 milliamps flows for 3 minutes calculate the charge transferred.

4. A capacitor of $10 \mu\text{F}$ has a p.d. across it of 40 volts. If it is discharged in 0.2 seconds find (a) the charge stored in the capacitor, and (b) the average value of the current during discharge.

Practical Puzzle 5. A switch which vibrates to and fro 50 times a second is used to connect a capacitor alternately to a 10 volt battery and a millimeter (Fig. 65). The meter indicates that an average current of 10 mA is passing. Assuming that the capacitor is fully charged and then fully discharged each time the contacts are made, find

- the charge passing through the meter every second,
- the charge passing through the meter every $\frac{1}{50}$ th second,
- the number of coulombs given to the capacitor during each charge,
- the p.d. across the capacitor when fully charged, and
- the value of the capacitance.

(Hint: current is the rate of flow of charge.)

The Volt

Alessandro Volta (1745–1827) inaugurated the era of the electric current by his invention of the first electric battery—the voltaic pile. One day he placed a piece of tin foil on the tip of his tongue

and a silver coin at the back of his tongue. When he connected these metals by a wire he noted a sour taste. The first voltaic cell had been produced! Later he tried a variety of different metals (electrodes) in different liquids (electrolytes) to see which gave the best results (Book 2, page 128). Volta was invited by Napoleon to demonstrate his invention in Paris, and the Royal Society of London published his report of the voltaic pile in 1800. Volta is also credited with the invention of the gold-leaf electroscope.

Joules per Coulomb

We saw in Chapter 2 that when a conductor was charged *the work done on every unit of charge* was a measure of the *potential difference* between the conductor and earth. The following model illustrates the same relationship for particles on the move.

Model 3.3. A vacuum cleaner can be used to blow table tennis balls up through a tube (Fig. 66). In this way they gain potential energy of (say) V joules per ball. They are then stored in a box at the top of the tube. The potential energy at the bottom of the tube is taken as zero, so that the p.d. between the balls in the box and those at the bottom is V joules per ball.

A hole is cut at the end of the box to allow the table tennis balls to fall out one at a time. They gain kinetic energy as they fall and this is used to turn a paddle wheel. The energy transferred to the paddle wheel can then be used to do work of various kinds. Having given up some of their kinetic energy, the balls are directed into the lower end of the tube to be re-energised by the jet of air.

If the hole in the box is closed the balls will pile up in the box and no further energy will be transferred, although there is a p.d. of V joules per ball between the top and bottom of the tube. If the vacuum cleaner is now switched off the model will resemble a charged capacitor.

When a battery and bulb are connected as shown in Fig. 67, electrons move round the circuit. As they pass through the battery they gain potential energy. The 'energised' table tennis balls were

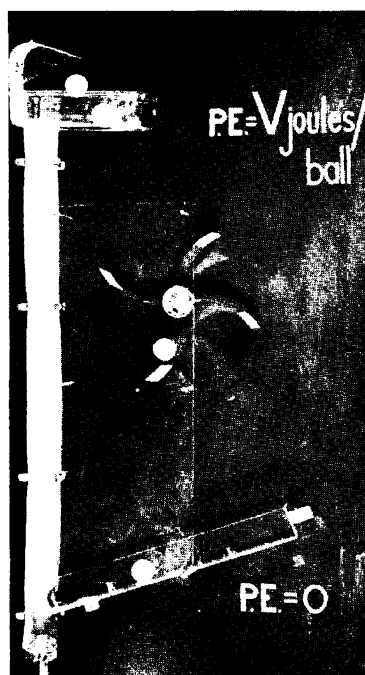


Fig. 66

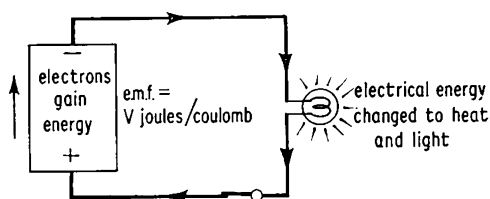


Fig. 67

in a *gravitational field*, which caused them to accelerate until they collided with the paddle wheel, when some of their energy was transferred to the wheel. The 'energised' electrons are in an *electric field*, and so are accelerated until they collide with the positively charged atomic nuclei in the metal. Some of their energy is then transformed to heat in the bulb. Between collisions they are again accelerated. Eventually they return to the positive terminal

to be 're-energised'. The gain in energy as they pass through the battery is measured in joules per unit charge, that is, joules/coulomb.

If the p.d. across the bulb is (say) 3 volts, this means that 3 joules of electrical energy are transformed to heat and light for every coulomb that passes through it.

If the switch is open (corresponding to the outlet hole in the box being closed) charges cannot flow continuously round the circuit and the electrons 'pile up'. There is still a difference of potential across the battery; it is called the electro-motive force (e.m.f.) of the battery.

Practical Puzzle 6. You are given a rheostat, ammeter, voltmeter, immersion heater, thermometer, stop watch and polystyrene cup containing a known mass of water (Fig. 68). How could you check one reading on the voltmeter to see if it agrees with the definition of the volt? (Specific heat of water = $4200 \text{ J/kg}^\circ\text{C}$.)

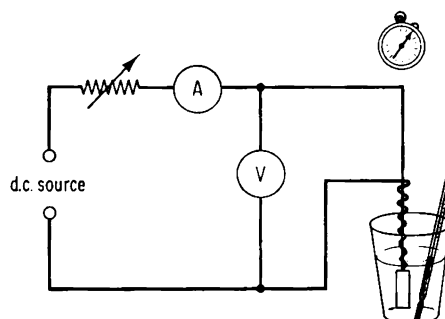


Fig. 68

Problem 7. What is the voltage used for domestic lighting circuits? Is there a p.d. between the contacts of a light switch when it is (a) open, (b) closed?

Problem 8. An electric bulb rated at 12 joules per coulomb passes 2 coulombs per second. What is

- the p.d. across the bulb,
- the current through the bulb,
- the energy transferred per coulomb, and
- the energy transferred per second?

The Ohm

Georg Simon Ohm (1787–1854) was the son of a German mechanic who was determined that his son should learn mathematics and physics. At the age of 16 the boy went to university to study these subjects, but after two years funds ran out and he was compelled to take up a teaching post in Switzerland. But his heart was set on a university career and after some time in Switzerland he was able to return and complete his course.

He wanted to stay on in the university but his work was not considered good enough. He returned to Germany to teach mathematics at the Gymnasium in Cologne, but he also continued

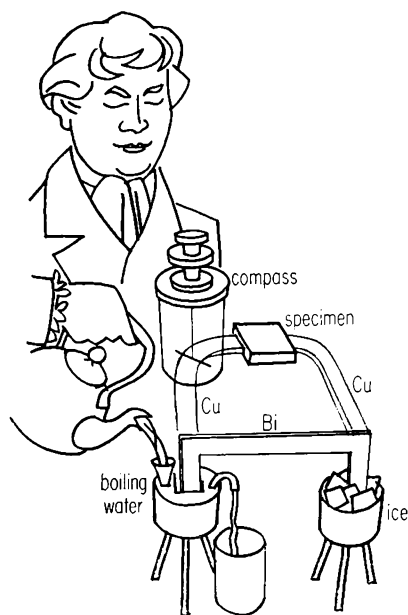


Fig. 69

his research work on quantitative electricity. At that time the electrical terms in use were vague and woolly, and so he determined to do something about it. He knew that the quantity of heat flowing through a conductor was dependent on the temperature difference across it (Book 2, page 45), and he thought that perhaps electricity might behave in a similar way. In his early experiments he used voltaic cells but as he found that they would not supply a sufficiently constant source of e.m.f. he turned to copper/bismuth thermocouples. One junction he kept in melting ice and the other he heated with boiling water (Fig. 69). He measured the current by the deflection of a compass needle suspended over one of the conductors (cf. Book 2, page 128), and noted how this current varied when other thermocouples were added.

He published his results in 1826 and the Minister of Education, who did not approve of planned experiments, immediately accused him of heresy and pronounced him 'unworthy to teach'. So Ohm lost his position because his work was too experimental. Earlier he had failed to be accepted by the university as his work was not sufficiently experimental!

Ohm was dismayed and bitterly disappointed, and for many years no one seemed to take any interest in his work. Gradually, however, his book became known outside Germany and in 1841 the Royal Society of London awarded him its highest honour—the Copley medal. This forced his own people to recognise him, and in 1849 when he was over 60 years of age Ohm was appointed to the professorship in Munich University which he had so long coveted.

If you have not already made Ohm's discovery you can do so in the next experiment.

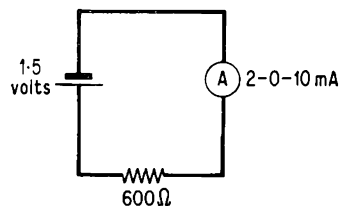


Fig. 70

Experiment 3.4. Use a dry cell (e.m.f. = 1.5 volts) in the circuit shown and note the current through the resistor (Fig. 70). Add another similar cell in series (e.m.f. now = 3.0 volts) and again note the current. Repeat this operation with 3 and then 4 cells in series.

e.m.f. (V)	current (I)	$\frac{V}{I}$
1.5		
3.0		
4.5		
6.0		

What can you say about the third column? What does this tell you about the relationship between V and I ? The ratio V/I is called the *resistance* of the circuit. If the p.d. is in volts and the current in amperes, the resistance is in *ohms*.

List some of the things which have been kept constant during this experiment and state which you think are relevant.

Complete the following statement:

Ohm's law states that in a conductor at constant . . . the current is . . . proportional to the potential difference across it. (9)

$$\frac{V}{I} = R$$

Ohm's law does not apply to all conductors but it is valid for practically all metals provided the temperature remains constant. Semi-conductor diodes and thermionic valves are examples of non-ohmic conductors.

Problems

10. Write down an expression for (a) V in terms of I and R , (b) I in terms of V and R .

11. A headlamp bulb takes 3 amperes when the p.d. across it is 12 volts. Find the resistance of the bulb.

12. If 10 amperes flow through 2.5 ohms, what is the p.d. across the resistor?

13. An electric radiator has a resistance of 60 ohms. What current will flow through it if it is wired to a 240 volt supply?

Resistors in Series

Although wires have some resistance, it is normally so small that for our purposes we can ignore it.

Problem 14. In the circuit shown in Fig. 71 two resistors are connected in series. What is the current through the 3 ohm resistor? What is the current through the R ohm resistor? What is the value of R ? What is the total voltage V volts? If a single resistor allowed the same current to flow when the same voltage was applied, what would be its value? How is the value of this single resistor related to the value of the two resistors in Fig. 71?

Problem 15. Use the same reasoning as you used in the last problem to find the equivalent or total value (R_s) of two resistors (R_1 and R_2) in series (Fig. 72).

Resistors in Parallel

Problem 16. In the circuit shown in Fig. 73 how are I_1 , I_2 and I related? What are the values of I_1 , I_2 and I ?

If the applied voltage were V volts what would be the values of I_1 , I_2 and I in terms of V and the resistances given?

If we call the total or equivalent resistance R_p then $I = \frac{V}{R_p}$. Equate this to the value of I you have just found and hence find R_p .

Problem 17. Using the same reasoning as in the last problem write down values for I_1 , I_2 and I in terms of V , R_1 and R_2 (Fig. 74).

If the total resistance is R_p , again $I = \frac{V}{R_p}$. Equate this to the value of I you have just found; hence derive an expression for R_p in terms of R_1 and R_2 .

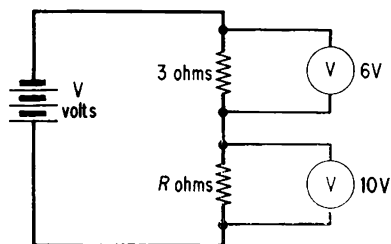


Fig. 71

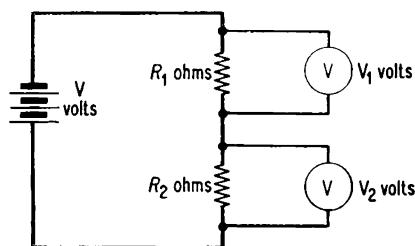


Fig. 72

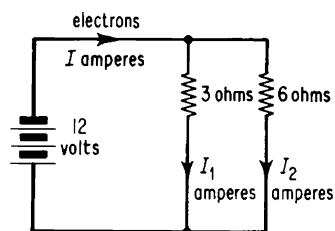


Fig. 73

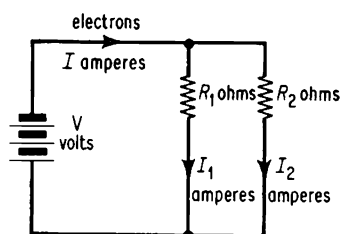


Fig. 74

Resistors in Series and Parallel

Complete the following statements.

When two resistors of R_1 ohms and R_2 ohms are connected in series the equivalent resistance R_s is given by

$$R_s =$$

When two resistors of R_1 ohms and R_2 ohms are connected in parallel the equivalent resistance R_p is given by

$$\frac{1}{R_p} =$$

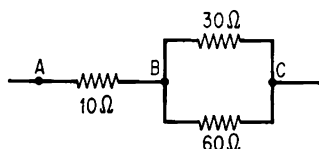


Fig. 75

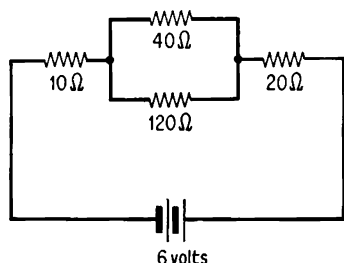


Fig. 76

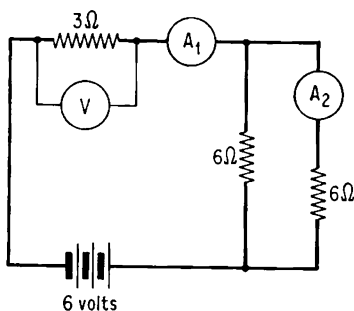


Fig. 77

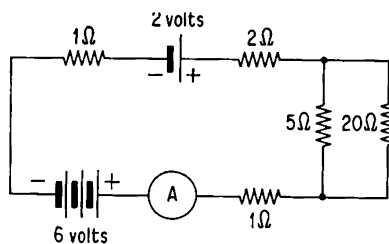


Fig. 78

Practical Puzzle 18. If two 600 ohm resistors were connected in series, what would be the total resistance? How would you check this experimentally?

If the same resistors were wired in parallel, what would the total resistance be? How could this be checked by experiment?

Problems

19. What is the total resistance of three resistors R_1 , R_2 and R_3 (a) in series and (b) in parallel?

20. (i) Calculate the total resistance for each of the following groups of resistors when they are connected in series. (a) 2 ohms and 4 ohms, (b) 15 ohms and 45 ohms, (c) 3 ohms, 4 ohms and 6 ohms.

(ii) Calculate the total resistance for each of the above groups when the resistors are wired in parallel.

21. What is the total resistance between B and C in Fig. 75? What is the total resistance between A and C?

22. What current will flow through (a) the 10 ohm resistor, (b) the 120 ohm resistor in Fig. 76? What will be the p.d. across (i) the 40 ohm resistor, and (ii) the 20 ohm resistor?

23. Two wires of the same material have the same length and cross-sectional area. When 1 volt is applied to one of them one ampere flows. Find the current if the same voltage were applied to the two wires (a) in series, (b) in parallel.

24. How does the resistance of a wire depend on (a) its length, (b) its cross-sectional area?

Use these facts to explain why two resistors (i) in series have a greater resistance, and (ii) in parallel have a smaller resistance than either resistor alone.

25. Should a good voltmeter have a high or low resistance? Why? Is the same true for a good ammeter? Explain your answer.

26. If the voltmeter V has an extremely high resistance (Fig. 77) and the ammeters have very low resistances, what will be the readings in V , A_1 and A_2 ?

27. In Fig. 78 what will the meter read if it has negligible resistance? What current will flow through the 20 ohm resistor? What will be the p.d. across the 2 ohm resistor?

Insert arrows showing the direction of the electron flow in the circuit.

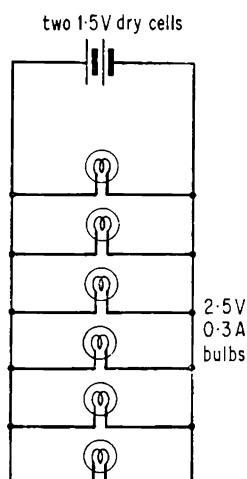


Fig. 80

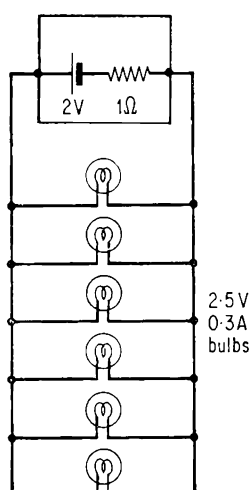


Fig. 81

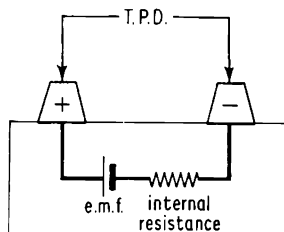


Fig. 82

28. If all the ammeters in Fig. 79 have negligible resistances and all the voltmeters extremely high resistances, state the readings in all the meters.

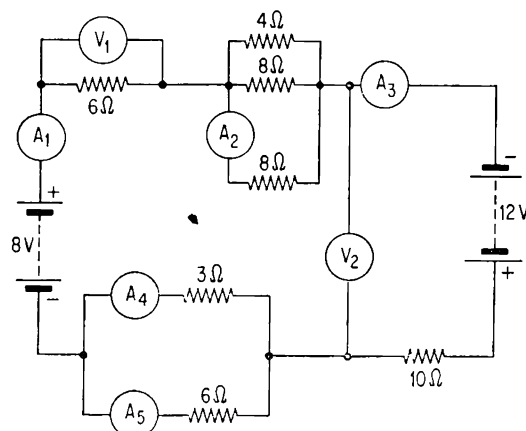


Fig. 79

Internal Resistance

Experiment 3.5

(i) Use two 1.5 volt dry cells to supply the circuit illustrated in Fig. 80. Screw the bulbs into their holders one at a time and report any change in the brightness of the glowing bulbs as more are added to the circuit. What is happening (a) to the p.d. across the bulbs, and (b) to the current taken from the cells as more bulbs are connected?

(ii) Repeat this experiment, using a large fully charged 2 volt accumulator in place of the two 1.5 volt cells. Do you observe any difference in the results?

(iii) Now insert a 1 ohm resistor in the circuit as shown in Fig. 81 and again repeat the experiment. How has the addition of this resistor affected your results? How does this circuit compare with the original circuit supplied by the dry cells? Put a voltmeter across the terminals of the accumulator and see what happens when the bulbs are disconnected one by one. Does the reading vary? Does the p.d. across the bulbs vary?

The results of the above experiment suggest that a dry battery behaves rather like an accumulator, maintaining a constant e.m.f., connected in series with a resistor. When a current is taken from the battery some of the energy (from chemical reactions inside) is used to drive the current through the battery itself. The greater the current taken the greater is the energy required for the 'internal operation'.

For simplicity you can think of a cell as if it consisted of a constant source of e.m.f. in series with a resistance (Fig. 82). Although this is a fanciful picture, it helps us to see that the voltage across the terminals (sometimes called the terminal potential difference or t.p.d.) is not necessarily the same as the e.m.f. The difference is

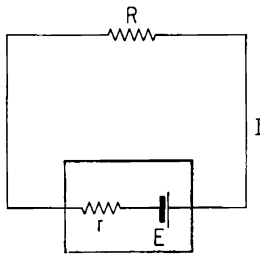


Fig. 83

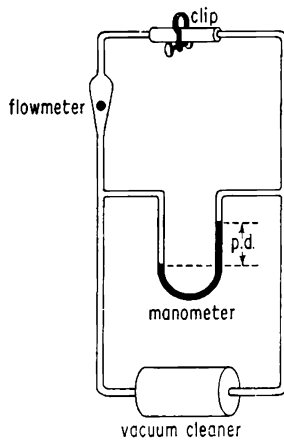


Fig. 84

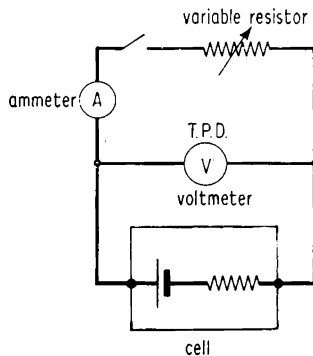


Fig. 85

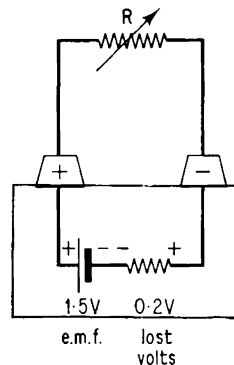


Fig. 86

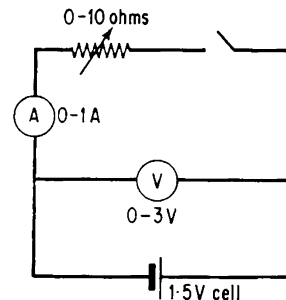


Fig. 87

sometimes called the 'lost volts'. The resistance is really part of the cell itself and is called the *internal resistance*. In general dry cells have a much greater internal resistance than accumulators. For any particular type of cell the *larger* the cell the *smaller* the internal resistance.

A cell might be considered as an energy transformer in which chemical energy is changed to electrical energy. Like other machines it is not 100 per cent efficient, and the difference between the input energy per coulomb (e.m.f.) and the output energy per coulomb (t.p.d.) is the 'lost volts'. In Fig. 83 E = e.m.f. I = current. R = external resistance. r = internal resistance.

Input	'Lost volts'	Output
Energy supplied by the cell per coulomb	Energy used in the cell per coulomb	Energy transformed in the external load per coulomb
E	$=$	$Ir + IR$

Model 3.6. Here is an analogy which may help you to think about internal resistance. The manometer in Fig. 84 reads the pressure difference (p.d.) across the inlet and outlet pipes. The vacuum cleaner is supplied by a variable transformer.

When the screw clip is tightened so that no air flows through the rubber tube, the p.d. across the vacuum cleaner is high. If the clip is opened, air flows round the circuit and the p.d. falls. The flow can be measured by a flowmeter (e.g. a rotameter, size 7A with a type A float). By adjusting the screw clip you can alter the air flow and study the change of p.d. with flow.

In the electrical circuit (Fig. 85) the t.p.d. changes as the current taken from the cell alters.

Problem 29. What will be the t.p.d. across the cell shown in Fig. 86? Will the current increase or increase as R is increased? Will the t.p.d. then increase or decrease?

Experiment 3.7. Connect a 1.5 volt dry cell in the circuit shown in Fig. 87. With the switch open note the voltmeter reading. This is numerically equal to the e.m.f. of the cell. Close the switch and adjust the rheostat to give a current of (say) 0.2 amperes and again

note the voltmeter reading (t.p.d.). Find the lost volts. Repeat this procedure for various arrangements up to (say) 1 ampere. Complete the table and find the average value of internal resistance.

Do not keep the switch closed for more than a few seconds at a time, and leave at least half a minute between readings to reduce the effects of polarisation.

e.m.f. of cell =

Current (I)	t.p.d.	Lost volts (V)	Internal resistance $r = \frac{V}{I}$

Project 3.8. Find the internal resistance of various laboratory power packs. Be careful not to exceed the stated maximum current.

Problems

30. A thoughtless motorist tries to start a car while the headlamps are switched on. Why do the lamps go dim?

31. Why are dry cells not used for car batteries?

32. A battery consists of two cells connected in series. Each has an e.m.f. of 1.5 volts and internal resistance of 1 ohm. What will be the measured terminal voltage of the battery if the voltmeter used has a resistance of (a) 10 ohms, (b) 1000 ohms? Which is the better meter?

33. (a) A cell of e.m.f. 1.5 volts and internal resistance 2 ohms is connected to a 3 ohm resistor. What will be the current?

(b) Two such cells are wired in series with the same resistor. Find the current.

(c) If the cells were connected in parallel, what would be the current in the resistor?

34. A 2 volt accumulator has an internal resistance of 0.1 ohm. What value of external resistor will limit the current to 2 amperes? What will be the 'lost volts'?

35. A 1.5 volt cell with 1 ohm internal resistance is connected in a circuit which contains other sources of e.m.f. A high resistance voltmeter across the terminals of the cell reads zero. Give a possible explanation.

36. A 12 volt car battery which is discharged has a total internal resistance of 0.6 ohms. A 20 volt charger is to be used to recharge the battery at 2 amperes. What additional resistance will be required?

37. A small gas-lighter element has a resistance of 0.2 ohms. You are given five dry cells, each with an e.m.f. of 1.5 volts and internal resistance of 1 ohm. Would you connect the cells in series or parallel to obtain the greatest current through the element? Why is one very large cell normally used for this purpose?

38. When a 1.5 volt dry cell is short-circuited 3 amperes flow. When a 2 volt accumulator is short-circuited 200 amperes flow. What is the internal resistance of each? What harm may be done by short-circuiting an accumulator?

39. If you are given a 3 volt torch battery and a 9 volt transistor radio battery, how would you obtain the maximum e.m.f.? If the two positive terminals were connected together, what would a voltmeter connected to the two negative terminals read?

If the voltmeter was then removed and the negative terminals of the two batteries were then also joined together, what would happen?

40. You are given 5 cells, each of e.m.f. E volts but with different internal resistance. They have to be used to drive currents of 1, 3 and 5 units through a resistor. Draw diagrams showing how you would connect them.

41. An ammeter of negligible resistance reads 1 ampere in the circuit shown in Fig. 88. If the e.m.f. of the battery is 8 volts, what is its internal resistance?

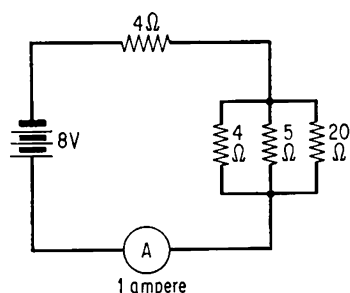


Fig. 88

The Watt

James Watt (1736–1819) was born in Greenock. His main contribution to science was not in electricity but in mechanical engineering (Book 2, page 138). He produced the modern condensing steam engine which made the Industrial Revolution possible. When his engines were used to replace horses in the mines, potential customers wanted to know how many horses one engine could replace. As Watt had to find a unit of power which he could use to indicate this, not surprisingly he invented the *horse-power* (Book 3, page 103). This unit is now gradually going out of use, but the modern unit of power honours the man who suggested it. The *watt* is a rate of working of 1 joule per second. It can be used to measure the rate of transforming every kind of energy.

Energy and Power

An electric current is used to transfer energy from one place, usually a power station, to another, for example a home or factory. It is this energy which the consumer pays for.

Consider for a moment the model illustrated on page 37. The energy transferred to the wheel depends on the number of table tennis balls which fall on the wheel (quantity), and on the height of the balls (i.e. the potential difference).

In the electrical case the energy transferred depends on the quantity of charge (Q) and the p.d. (V). This, of course, follows from the definition of the volt.

$$\text{p.d.} = \frac{\text{energy transferred}}{\text{charge}}$$

$$\text{energy transferred} = \text{charge} \times \text{p.d.}$$

$$E = QV = ItV$$

Labels: joules, coulombs, volts, amperes, seconds

In Model 3.3 we might take the speed of the wheel as an indication of the power (rate of transfer of energy). This will depend on the p.d. and on the number of balls which fall every second. In the electrical case, power depends on p.d. and on the number of charges passing per second, i.e. current.

$$\text{Power} = \text{energy transferred per second}$$

$$P = \frac{E}{t} = \frac{ItV}{t} = IV$$

$$P = IV$$

Labels: watts, amperes, volts

Problems

42. If a current of I amperes through a resistor of R ohms produces a p.d. across the resistor of V volts, show that the rate of production of heat (power) may be given by IV , I^2R or V^2/R .

43. What current does a 60 watt lamp take from a 240 volt supply?

44. What is the resistance of a 6 volt 12 watt lamp?

45. A 2 kW heater takes 20A. What is the supply voltage?

46. Find the resistance of a 60 watt and of a 150 watt lamp, each operating at 240 volts.

47. How many joules of electrical energy are transformed in a 6V 0.5A bulb every second?

48. A 1 kW radiator operates from 250V mains. What is its resistance, and what current does it take? What resistance would you have to put in series with it to reduce the power of the radiator to 500W? What would be the power taken from the supply then?

49. Calculate the power in each of the following cases.

(a) A 60 ohm heater on a 240V supply.

(b) A 12V accumulator delivering 5A.

(c) A discharge in 1 millisecond of 0.02 coulombs at 20 kilovolts.

(d) A 5A current in a 20 volt heater coil.

50. A 12 volt heater taking 4 amperes is immersed in 200 grammes of water at 15°C contained in a polystyrene cup. How long will it take to raise the temperature of the water to 25°C (specific heat of water = $4200\text{ J/kg}^{\circ}\text{C}$)?

51. If a 240 volt immersion heater can, in 2 minutes, bring to the boil 1 kg of water originally at 40°C , find the resistance of the heater.

52. A 500 watt toaster operates on 250 volt mains. Find (a) the resistance, (b) the current taken, (c) the heat produced in 10 minutes.

53. A 2 volt accumulator has a capacity of 100 ampere-hours. It should deliver 10 amperes for 10 hours or 5 amperes for 20 hours before being discharged. How much energy (in joules) can be stored in this accumulator?

54. An electric motor is rated at 250V 4A (1 kW). If it is 70 per cent efficient, how much heat is produced in it in 10 minutes?

55. If a 12V 36W bulb has to be used on a 20V supply, what series resistance is needed?

56. Thirty stage lights (each 240V 240W) are to be dimmed by a rheostat. If the current has to be reduced to one third of its original value, find the resistance required. What power must it be able to dissipate?

57. A 100 ohm radio resistor is rated at 2 watts. What is the maximum current permissible in this resistor? What is then the p.d. across it?

58. A resistor of 1 kilohm has to carry 50 mA. Would you choose a 2W or 5W resistor? What would be the voltage across it?

59. If a capacitor is charged to 1000 volts and then discharged through a 100 ohm resistor, a certain amount of heat is produced. If a 50 ohm resistor had been used would the heat produced have been (a) the same, (b) half, (c) a quarter, (d) double or (e) four times as great?

60. Find the energy transformed when 3 coulombs move through a p.d. of 50 volts.

61. How much energy is gained by an electron moving through a p.d. of 2×10^6 volts (charge on electron = 1.6×10^{-19} coulombs)?

62. 700 coulombs pass through a 12 volt battery to start a Mini. How much energy is used? If the car has a mass of 700 kilogrammes, how high could this amount of energy raise it against gravity? If the car took 3.5 seconds to start, find the average current and power.

63. If a lightning flash discharged 20 coulombs through 10^9 volts in 10^{-2} seconds, find the average current, energy transformed, and power.

64. Two 12 volt 24 watt bulbs are connected in parallel across a 12 volt battery. What current will be taken from the battery?

If the bulbs were connected in series, what current would flow? Would you expect the actual current to be greater or less than the calculated answer? Why?

65. If a p.d. of 20 volts produces a current of 5 amperes in a resistor find (a) the charge passed and (b) the energy transformed in 1 minute.

66. A current of 2 amperes flows in part of a circuit across which there is a p.d. of 30 volts. How long will 10 coulombs take to pass a point in the circuit? How long will it take for 600 joules to be transformed?

67. A dozen 20 volt lamps are to be used on a Christmas tree. How would you wire them to operate from 240 volt mains? If each lamp takes 0.3 amperes, what is the total energy transformed in 20 minutes?

68. Two tungsten lamps are labelled 24W. One is for 12V and the other for 240V operation. Which takes more current? Which has the longer filament? Which has the thicker filament? Which will use more energy per second? Find the resistance of each filament.

69. If the current in a wire is doubled, what difference would you expect in the heat produced per second? What assumption are you making?

70. Two bulbs marked 100V 100W are connected in series across a 240V supply. If their resistance does not alter, what would now be the power dissipated in each?

71. A 3-way adaptor is fitted to a 13A socket on a 250V mains supply. If a 2 kW fire, 1 kW toaster, and a vacuum cleaner with a resistance of 125 ohms are all operating from the socket at the same time, what current is being taken?

72. The element of an electric radiator burns out near the end and so you remove a couple of turns and connect up the remainder of the element to the supply. Will the shorter element give more or less heat per second? Explain.

73. State how the rate of production of heat would alter in an electric radiator if

(a) the resistance were doubled and the current remained constant

(b) „ „ „ „ „ voltage „ „

(c) „ current „ „ „ resistance „ „

(d) „ „ „ „ „ voltage „ „

(e) „ voltage „ „ „ current „ „

(f) „ „ „ „ „ resistance „ „

74. A lift of mass 100 kg is raised 60m in 40 seconds. Find the efficiency if it takes 100A from 250V supply.

Project 3.9. Measure the input power of an electric motor as it raises a load. Measure the time taken to raise the load, and hence find the efficiency of the motor.

Counting the Cost

A joule is the amount of energy supplied when 1 watt is taken for 1 second. 1 joule = 1 watt-second. As this is such a small quantity, electrical energy is sold in a unit which represents the energy used in an hour at a rate of 1000 watts. This is the Board of Trade 'unit' of electrical energy—the kilowatt hour (kWh). How many joules are there in 1 kWh? (75)

Project 3.10. Read your kilowatt hour meter at home and record the energy used each day for a week. Calculate the cost each day at twopence per unit.

Problems

For the following problems assume that electricity costs two-pence per kilowatt hour.

76. *A radiator is rated at 2 kW. How much will it cost to run it for 10 hours?*

77. (a) *Compare the cost of running a 3 kW immersion heater for 5 hours and a 100W lamp for 100 hours.*

(b) *For how long could you run a 100W lamp for the price of a match? Assume 50 matches cost threepence.*

78. *A 2 kW electric kettle contains 2 kg of water at 20°C. How long will it take to bring it to the boil? What will it cost to boil the water? If the kettle were left switched on once the water boiled how much longer would it take to boil it dry? How much more would it cost? (Specific heat of water 4200 J/kg°C; latent heat of water 22.6×10^5 J/kg.)*

79. *Estimate how much it would cost to provide you with hot water for a bath, using an electric immersion heater.*

80. *Estimate the annual cost of illuminating the Forth Road Bridge by sodium vapour lamps. State the assumptions you make.*

81. *Compare the cost of running four electric storage heaters each rated at 3 kW for 12 hours a day at 0.8d. per kilowatt hour and six 2 kilowatt heaters each in use for an average of 6 hours a day at 2d. per kilowatt hour.*

82. *Discuss why it can cost four times as much to boil a litre of water in a kettle on a hot plate as to boil it in an electric kettle.*

83. *The bulb in a torch is marked 2.5V 0.3A and the battery, which lasts for 3 hours, costs one shilling. What is the cost of 1 kWh?*

84. *Discuss the statement, 'An 80W fluorescent tube is cheaper to run than an 80W tungsten lamp'.*

85. *Do you pay for electric charge, electric power or electric energy?*

Wiring in Your Home

There are normally at least two separate circuits in a house, the lighting circuit with a 5A fuse and the power circuit with a 30A fuse. Additional circuits are necessary for immersion heaters, electric cookers and electric central heating systems.

In the case of the 13A ring mains circuit illustrated in Fig. 89, each plug is also fitted with a fuse. This is usually made of a tin-lead alloy or thin tinned copper wire. Should the current exceed a certain value the fuse wire heats up and melts, thus breaking the circuit. It is important to choose the correct fuse if each piece of equipment is to be protected against damage by too heavy a current. A TV set, which normally takes less than 1 ampere, should be fused at 2 amperes and not, for example, 13 amperes. Fuses for ring mains are supplied in four ratings, 2A (blue), 5A (grey), 10A (yellow) and 13A (brown). The fuse used for each appliance should be slightly larger than the normal current.

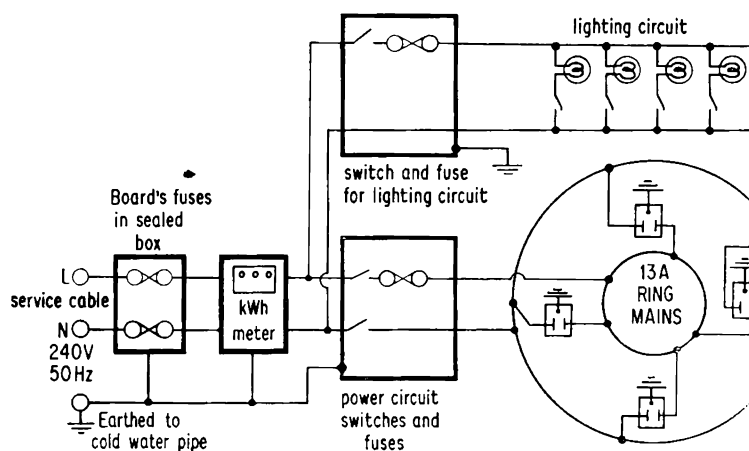


Fig. 89

Problem 86. Find the current and best fuse to use for each of the following 240V appliances

Appliance	Power	Current	Fuse
Convactor	3 kW		
Kettle	2 kW		
Radiant heater	1.5 kW		
Slide projector	1 kW		
Electric iron	800W		
Vacuum cleaner	600W		
Hair dryer	500W		
Cine projector	300W		
TV set	200W		
Electric blanket	150W		
Refrigerator	120W		
Table lamp	75W		

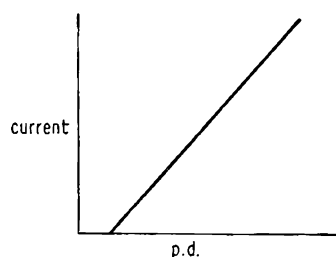


Fig. 90

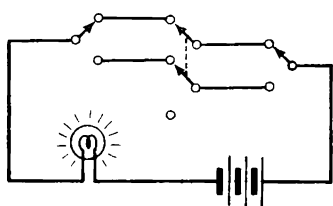


Fig. 91

Additional Problems and Puzzles

Practical Puzzle 87. How would you use a 1.5 volt cell, an ammeter and a voltmeter to find the resistance of a 3.5V 0.3A bulb? Would you expect it to be 11.7 ohms? Explain your answer.

Practical Puzzle 88. Fig. 90 shows how the current through a copper sulphate cell varies with the p.d. between its two platinum electrodes. Is its resistance ohmic? Can you explain why the graph does not go through the origin?

Practical Puzzle 89. Can you complete the circuit in Fig. 91 to produce a system in which the bulb can be switched on or off from any one of three switches?

Problems

90. Why are you less likely to get a shock from a faulty piece of apparatus which has an earth wire fitted than from one with no earth?

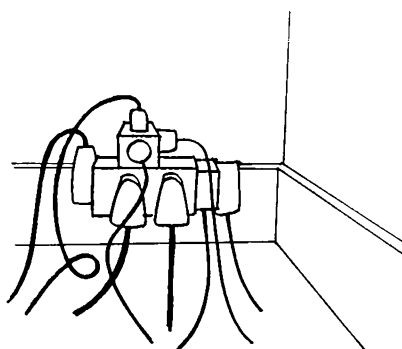


Fig. 92

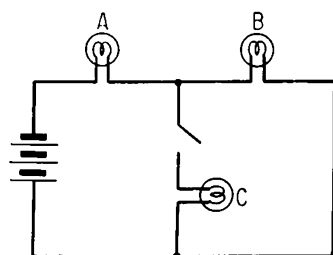


Fig. 93

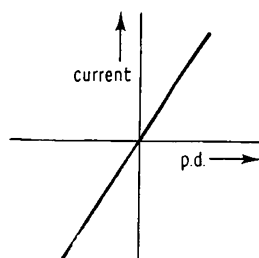


Fig. 94

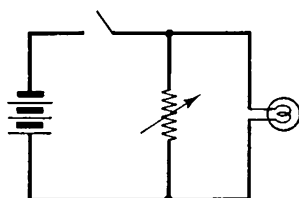


Fig. 95

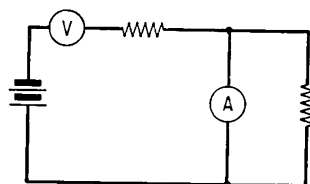


Fig. 96

91. Draw a sketch showing how you would wire a bench with 3 pairs of terminals, each giving 12V from a 12V battery. If the internal resistance of the battery was 0.2 ohms and a current of 3 amperes was taken from one of the terminals and 7 amperes from the other, what would be the p.d. across the third pair of terminals?

92. Why is it bad practice to use adaptors on adaptors on adaptors? (Fig. 92)

93. Three identical bulbs A, B and C are connected to a battery as shown in Fig. 93. What will happen to the brightness of A and B when the switch is closed?

94. Two bulbs marked 6V 0.3A and 6V 0.04A are connected in series to a 12V battery. What will happen? Explain your answer.

95. Draw a circuit in which three 240V bulbs are connected to a 240V supply in such a way that one switch controls one bulb and another switch operates the other two.

96. A convector has three identical elements. Draw diagrams showing how they could be wired to give five different rates of heating. (Hint: not all the elements need be used for each setting.)

97. A 'megaton of T.N.T.' is used as a measure of energy in nuclear bombs. It is equivalent to 4×10^{15} joules approximately. What is the energy released by a megaton bomb expressed in kilowatt hours? What would this amount of electrical energy cost at 2d. a unit?

98. Why is a bathroom radiator switch often controlled by a cord?

99. Fig. 94 shows the graph of current/p.d. for a component in a transistor radio set. Is the component ohmic? Can you suggest what the component is?

100. A dimmer has to be fitted to a quartz-iodine headlamp bulb. The circuit shown in Fig. 95 was suggested. Would the lamp be dimmed by such a resistor? Do you consider this to be a satisfactory arrangement? Explain your answer.

101. A pupil wired up the circuit shown in Fig. 96. Discuss it and describe what kind of readings you would expect in the meters.

102. An electric fire 'uses up a lot of electricity'. Can you restate this in more accurate language?

103. To generate your own electricity you jack up a bicycle and connect the rear wheel to a dynamo. You then pedal at a steady speed so that electrical energy is produced at a rate of 50 joules per second. How much electrical energy would be produced in 5 hours? What would this amount have cost at 2d a unit? Where did you get the energy?

104. You are given three ammeters, each with the same resistance and full-scale deflection of 3 amperes. Two have blank scales and one has a line marked on it to indicate a current of 1 ampere. If you were given a battery, two rheostats and some wire, explain with diagrams how you would calibrate all the meters to read 0-3 amperes in intervals of 0.25 amperes.

105. The chapter heading suggests that an electric current can be produced by heat. State one example of the generation of electricity by heat mentioned in this chapter.

Discuss the statement, 'Most of the electricity we use today is generated by heat'.

Summary of Chapter 3

1 ampere = 1 coulomb per second

$$I = \frac{Q}{t}$$

1 volt = 1 joule per coulomb

$$V = \frac{E}{Q}$$

1 ohm = 1 volt per ampere

$$R = \frac{V}{I}$$

1 watt = 1 joule per second

$$P = \frac{E}{t} = IV = I^2R = \frac{V^2}{R}$$

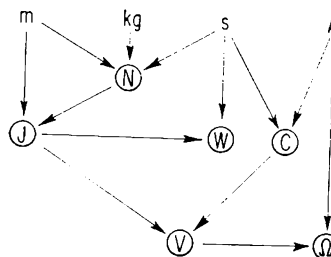
$$\text{Electrical energy (joules)} = QV = ItV = I^2Rt = \frac{V^2t}{R}$$

1 kilowatt hour = 3.6×10^6 joules

Resistors in series $R_s = R_1 + R_2 + R_3 + \dots$

Resistors in parallel $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$

S.I. Units



Visual Aids

Filmstrips: Electric Current₃₀ 5151.

Electricity in your home₃₀ 4702.

16 mm Films: Elements of Electrical Circuits₂₉ 20.3841.

Series and Parallel Circuits₂₉ 20.3872.

Electrons at Work₂₉ 21.7486.

What is Electric Current?₃₁ DC.2866.

Electricity and Heat₃₁ DF.572.

What is Electricity?₃₁ DF.571.

Electrons in Motion $\rightleftharpoons$ Chemical Change

CHAPTER 4

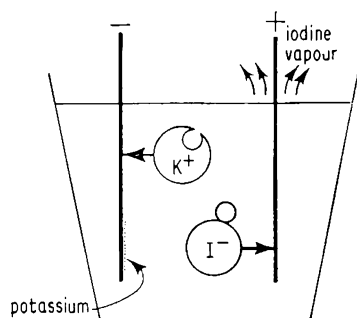


Fig. 97

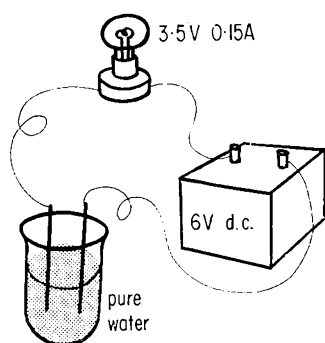


Fig. 98

When a length of wire is connected to a battery, charges flow through the wire causing it to heat up. We picture some of the electrons in the metal as being loosely held by the atoms, so that when an electric field is applied these *free electrons* move through the conductor. This is not a chemical change, since at the end of the day the metallic conductor is chemically the same as it was originally.

If two carbon rods are inserted in potassium iodide and connected to a d.c. supply, no current passes (Book 2, page 30). No charges are free to move. If, however, the crystals are strongly heated until they melt, we find that charges do move and that chemical changes occur (Fig. 97). In the liquid state, positively charged potassium ions move to the cathode and negatively charged iodide ions move to the anode.

Instead of heating the crystals of potassium iodide you may add water to form a solution in which ions are free to move. Substances which can be separated into oppositely charged ions, either by fusion or solution, are called *electrolytes*.

Chemical changes can also be used to *produce* a current in a conductor. Torch or transistor radio batteries are obvious examples (Book 2, chapter 11).

Practical Puzzle 1. Two carbon rods in distilled water are connected as shown in Fig. 98. What will happen? If sodium chloride is added, what difference will it make? Explain why this change takes place.

Michael Faraday (1791–1867)

Michael Faraday, who has been described as the greatest experimental philosopher the world has ever seen, was born in Surrey in 1791, the son of a blacksmith. He was brought up in a strict Protestant sect, of which he was a lay preacher. After having little formal education he started work at the age of 12 as a message boy in a bookseller's shop. He read avidly all the science books he could, attended some lectures by Sir Humphrey Davy in the Royal Institution and became so fascinated that he wrote to Davy asking for a job. One of the governors of the Institution, suggesting that he should be given the job of washing bottles, said, 'If he is any good he will accept the work and if he refuses he is no good for anything'. During his 45 years in the Royal Institution Faraday rose from lab assistant to Director of the Institution and Professor of Chemistry. So great was his fame that the Queen presented him with a house when he retired from the Institution.

Early in the 19th century Sir Humphrey Davy, using Volta's battery (page 36), had discovered two new elements, sodium and potassium. His fame had spread through Europe and in 1807 Napoleon presented Davy with a medal and 3000 francs, even though England and France were then at war! 'If two countries or governments are at war, the men of science are not', said Davy. 'That would indeed be a civil war of the worst description'.

In 1813 Davy and Faraday went to France, where they were warmly welcomed and allowed to travel freely through the country, which was still at war with England. They were even invited to an anniversary dinner at which a toast was proposed to the Royal Society of London. Their European tour lasted 18 months, during which time they met many famous scientists, including Volta, Ampère and Gay-Lussac.

Faraday was responsible for a series of most brilliant researches, particularly on electrolysis and electro-magnetic induction. Helmholtz said of him, 'A few wires and some odd bits of wood and iron seem to serve him for the greatest discoveries'.

Faraday has the rare distinction of having two units called after him; the farad (unit of capacitance) and the faraday (unit of electric charge). In addition many pieces of equipment bear his name; the Faraday cylinder, the Faraday tube, Faraday's cage, Faraday's disc, and Faraday's ice pail. The laws of electrolysis and of electro-magnetic induction, which he first stated, also carry his name, as do the Faraday effect and the Faraday dark space.

In addition to carrying out his researches, Faraday gave demonstration lectures to large audiences in the Royal Institution, and began the famous Christmas lectures for children. He produced many non-mathematical 'models' which help us to understand physical phenomena. He suggested that his work on electrolysis might be explained in terms of charged particles, and he developed the idea of fields and field lines to explain the effects of electric and magnetic forces.

It might be fitting to conclude this brief sketch of Michael Faraday with his own description of the ideal scientist. He should be 'enthusiastic, but careful, linking experiment with analogy, mistrustful of preconceived ideas, regarding a fact as more valuable than a theory, not hasty in generalisation and, above all, prepared to test his own opinions at every step both by consideration and observation'.

A Faraday lecture is given in several cities each year. This is always a first class demonstration lecture on contemporary developments based on Faraday's work. Look out for the posters!

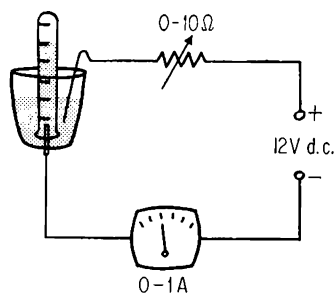


Fig. 99

Faraday's First Law

Experiment 4.1

(a) A simple voltameter can be constructed from a polythene food container and a piece of nickel plate made into a cylinder. The cylinder is bolted to the bottom of the container with a 4 mm terminal to form the negative electrode (cathode). The anode can be a copper strip (Fig. 99). Calibrate a test tube with a chinagraph pencil, in four equal volumes of (say) 5 cm³. Pour water into the

container and add a little dilute sulphuric acid to provide the ions necessary for conduction. Fill the test tube with acidulated water and invert it over the cathode.

(i) Connect the circuit as shown, and adjust the current to 1 ampere by altering the rheostat or sliding the test tube up and down on the electrode. Collect and test the gas liberated. What gas is it?

If the temperature and pressure remain approximately constant we can assume that the *volume* liberated is proportional to the *mass* of gas liberated.

(ii) Repeat the experiment, noting the time taken to obtain 1, 2, 3 and 4 volumes of gas when a constant current of 1 ampere passes. How does the volume and hence the mass liberated vary with time?

(iii) Repeat the experiment again, but now note the time taken for (say) two volumes of gas to be liberated by $\frac{1}{2}$, 1 and then 2 amperes.

(b) An alternative piece of apparatus_{N54} is illustrated in Fig. 100. This is, however, essentially demonstration equipment.

(c) A copper voltameter can also be used to study Faraday's first law. Two copper plates in a copper sulphate solution are used and the mass of the cathode found before and after each experiment.

Electrolysis

The mass of a substance liberated during electrolysis depends on the current (I) and the time (t). From your experimental results complete the following.

The mass liberated is . . . proportional to the current.

The mass liberated is . . . proportional to the time.

If 1 ampere flows for 1 second, the mass liberated is called the electro-chemical equivalent (z). Complete the following table.

When 1 ampere flows for 1 second the mass liberated = z kilogrammes

When I ampere flow for 1 second the mass liberated = kilogrammes

When I ampere flow for t second the mass liberated = kilogrammes

$$\begin{array}{c}
 \text{m} \qquad \qquad \qquad = \qquad \qquad \qquad z I t \\
 \text{kilogrammes} \qquad \qquad \text{kilogrammes} \\
 \qquad \qquad \qquad \text{per} \\
 \qquad \qquad \qquad \text{coulomb}
 \end{array}
 \begin{array}{l}
 \text{seconds} \\
 \text{amperes}
 \end{array}$$

As It is the total charge which has passed, we see that the mass of hydrogen liberated is directly proportional to this charge.

Faraday found that for hydrogen the mass per unit charge $\left(\frac{m}{It}\right)$ did not depend on the strength of the current or on the electrolyte. This can be explained by assuming that

(a) a quantity of charge corresponds to a definite number of electrons;

- (b) hydrogen ions are present in the electrolyte. These are hydrogen atoms minus one electron;
- (c) when hydrogen gas is liberated, the hydrogen ion gains one electron from the cathode and becomes electrically neutral.

One hydrogen atom is thus liberated by the passage of one electron, and so the number of atoms (mass) is proportional to the number of electrons passing (charge). By measuring both the charge (Q) and the mass (m) Faraday found the charge per unit mass for the hydrogen ion.

$$\frac{Q}{m} \text{ for hydrogen ion} = 9.6 \times 10^7 \text{ C/kg}$$

Problem 2. The mass of a hydrogen atom is $1.67 \times 10^{-27} \text{ kg}$. If 1 ampere flows for 5 minutes, what mass of hydrogen will be liberated by electrolysis? (1 coulomb = 6.24×10^{18} electrons.)

Electro-Plating

In the electrolysis of dilute sulphuric acid, hydrogen ions moved to the cathode, were discharged and liberated as hydrogen gas. In a copper sulphate solution we find that copper is deposited on the cathode. The metal ions have moved to the cathode, where they are discharged and deposited in the form of atoms of metallic copper (Fig. 101). In this way the cathode is copper plated. Chromium plating is effected in a similar way.

Electrons enter at the cathode, where hydrogen is released or metals deposited. Electrons leave at the anode, where oxygen is released or metals dissolved. Metals are sometimes refined by using an impure metal as the anode and depositing the pure metal on the cathode. Fig. 102 shows a copper refining plant in Zambia.

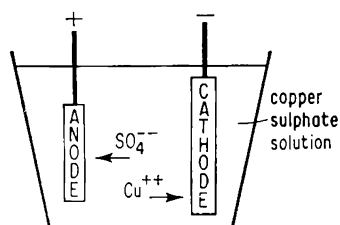


Fig. 101



Fig. 102

Project 4.2. You might like to grow a 'lead tree', using two carbon rods in a solution of lead acetate. Add a few grammes of lead acetate to a beaker of water and stir it with a glass rod previously dipped in acetic acid. The acid ensures a clear solution. A 6–12 volt supply is adequate.

Project 4.3. Here is a way to nickel plate a coin or a badge. First prepare the electrolyte from nickel sulphate (120 g), nickel chloride (27 g), boric acid (15 g) and 500 cm³ of water. Clean the coin thoroughly before connecting it to the negative terminal of a battery and use a strip of nickel for the anode. The current should be about half an ampere.

For the following problems take the electrochemical equivalent of copper as 3.3×10^{-7} kg/C.

Problems

3. What current is needed to deposit 1g of copper in two hours?
4. An ammeter reads 1 ampere when connected to a copper voltameter. In half an hour 0.66g of copper is deposited on the cathode. Is the meter correctly calibrated?
5. A boy uses an electrolysis experiment to calibrate an ammeter. He is in a hurry and uses a very large current so that some of the deposit flakes off. Will his calibration be high or low? Another boy washes the cathode in methylated spirits and burns it off so that some copper is oxidised. Will his calibration be high or low? Explain each answer.
6. A current of 2 amperes flows for 2 hours and deposits copper on 72 cm² of cathode. How thick is the plating? (The density of copper = 9×10^3 kg/m³.)
7. How long will it take for a current of 1 ampere to deposit 2 grammes of silver? (z for silver = 1.118×10^{-6} kg/C)
8. An atom of copper has a mass of 1.05×10^{-25} kg. During electroplating two electrons must be supplied for every copper atom deposited. If 2 amperes flows for 2 minutes, how much copper is deposited? ($1C = 6.24 \times 10^{18}$ electrons.) Check your results, using the electro-chemical equivalent.

Summary of Chapter 4

Faraday's First Law of Electrolysis

The mass of any element liberated or dissolved is proportional to the total charge that passes.

$$\frac{m}{It} = \text{constant } (z)$$

Visual Aids

16 mm Films: Electricity in Motion₃₁ 3DC.3199.
Electrolysis₃₁ DB.1.

Electrons in Motion $\rightleftharpoons$ Magnetic Field

CHAPTER 5

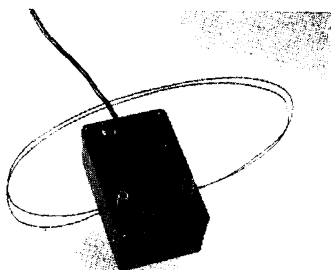


Fig. 103

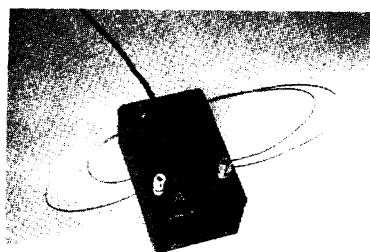


Fig. 104



Fig. 105

Force Between Moving Charges

From your experiments in electrostatics you discovered that a positive charge is attracted to a negative charge, whereas two like charges repel each other. In the following experiments you can study the effect of two streams of charges (electrons) moving in the same and then in opposite directions (cf. Book 2, Chapter 12).

Experiment 5.1. Connect two 50 cm lengths of fine insulated wire to a 2V accumulator or a low voltage supply_{N104} (Fig. 103). The d.c. output from this unit is too small for satisfactory results. Why does it not matter whether the current is d.c. or a.c. for this experiment?

Adjust the wires until they are lying parallel to each other and about 5 mm apart. Switch on for two seconds and observe any movement of the wires. Were the charges always moving in the same direction in the two wires?

Experiment 5.2. Repeat the last experiment with one wire twisted as shown in Fig. 104. Adjust the wires until they lie parallel to each other and close together. Switch on the supply for two seconds. The charges will now move in opposite directions. How do the wires move?

Demonstration 5.3. The above effects can also be demonstrated with the apparatus₂ illustrated in Fig. 105.



Fig. 106



Fig. 107



Problem 1. Draw the field lines round the conductors shown in Fig. 106 and Fig. 107 and then complete the following statements.

- currents in the same direction . . . each other;
- currents in opposite directions . . . each other;
- like static charges . . . each other;
- unlike static charges . . . each other.

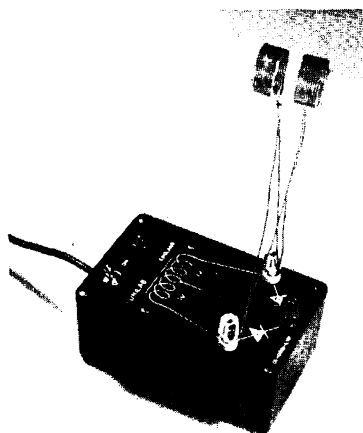


Fig. 108

The Ampere

As we have seen earlier, the ampere, in SI units, is defined in terms of the force between two very long parallel wires one metre apart. When the current in each wire is 1 ampere the force between the wires is 2×10^{-7} newtons per metre length. But the ampere had already been defined before SI units were introduced. By using the number 2×10^{-7} in this new definition, the size of the unit remains the same and only the way of defining it is altered.

Experiment 5.4

(i) Wind two small 10-turn coils and attach them to the 2 volt a.c. supply as shown in Fig. 108. A piece of Sellotape wound round the coils is helpful.

What happens when the current flows (a) in the same direction in each coil, (b) in opposite directions? Is the force acting between the coils greater or less than the force between two single wires?

(ii) Repeat the experiment but pass an iron bar through the coils and support it on a stand. How does this affect the force acting?

(iii) Reduce the voltage applied to the coils and hence the current through them and see if the force alters.

Magnets and Moving Charges

Demonstration 5.5. Using the Leybold fine beam tube (Fig. 3) or the Teltron e/m tube (Fig. 2), investigate the change in direction of the electron beam in a magnetic field. How is the direction of the force acting on the electrons related (a) to the direction in which the electrons are moving, and (b) to the direction of the field lines?

If we assume that the speed of the electrons is not altered, does the magnetic field cause them to accelerate? Is there then a force acting on the electrons?

Experiment 5.6. Try to devise experiments with magnadur magnets, some 26 gauge wire, a resistor (e.g. a bulb) and a low voltage power unit_{N104} (Figs. 109 and 110) to answer the following questions.

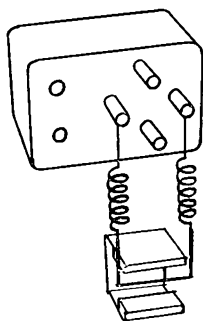


Fig. 110

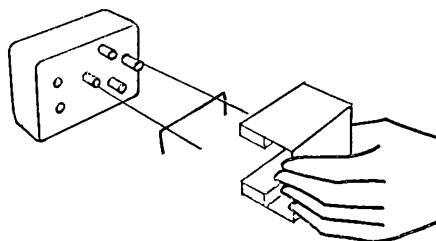


Fig. 109

What happens to the force on a conductor when

- (a) the current (I) is increased, and
- (b) the length (l) of the conductor (e.g. the number of turns of a coil) is increased?
- (c) the magnetic field (B) is increased,

How are the directions of the electron flow, magnetic field and motion related?

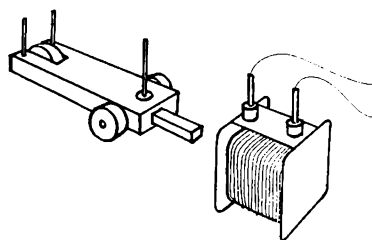


Fig. 111

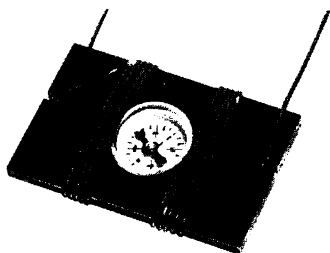


Fig. 112

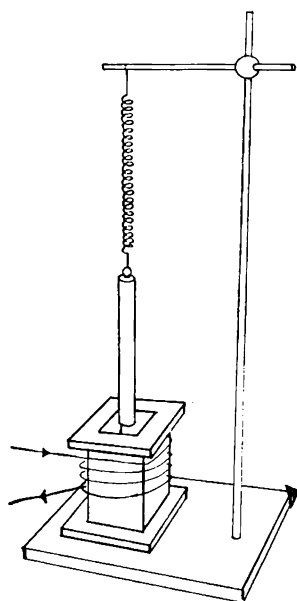


Fig. 113

Experiment 5.7

(i) Use one of the 10-turn coils from Experiment 5.4 and connect it to a low voltage supply. Bring a pole-faced magnet towards the coil. What happens? Does it matter whether the supply is a.c. or d.c.?

(ii) Using a d.c. supply find the effect of

- reversing the magnet.
- reversing the coil or the input to it.
- reversing both (a) and (b).

In the last two experiments you investigated the force acting on a current-carrying conductor in a magnetic field. *Does Newton's Third Law of Motion suggest there is another force acting? (2). If so, what is it? (3)*

Demonstration 5.8. Attach a bar magnet to a trolley and insert the magnet in a 600-turn coil. What happens when the coil is attached to a 12V d.c. supply? What difference does reversing the supply make? Does a force act on the coil? If so, how does it compare with the force acting on the magnet?

Project 5.9. Can you devise a scheme in which a current-carrying coil is fitted to one trolley and a permanent magnet to the other in such a way that Newton's Third Law can be demonstrated?

Project 5.10. If you are given a length of wire, soft iron bar, compass, d.c. source and rheostat, how could you show that the strength of the magnetic field depends on the *ampere turns*? Draw your circuit and show exactly how you position the compass and coil.

Meters

Galvanometers

A simple current reading device was used earlier to measure the current from a Voltaic pile (Book 2, page 128). You can make such a galvanometer from parts in the electromagnetic kit₉₂.

Experiment 5.11. Wind five turns of wire on either side of the compass as shown in Fig. 112. How should the needle point before a current flows in the coil? Why?

Connect the coils to a low voltage d.c. supply via a 100 ohm rheostat. Note how the deflection varies as the resistance in the circuit is altered. How would you calibrate this instrument as an ammeter? What do you think are the major disadvantages of this instrument?

Moving Iron Meter

When a current flows through a coil, the magnetic field produced will attract a piece of soft iron towards it (cf. Book 2, page 153, Fig. 320). If the current is increased, the pull on the iron will be increased. We can make use of this fact to measure the current.

Fig. 113 shows a primitive kind of moving iron meter in which the iron bar is suspended by a fine spring.

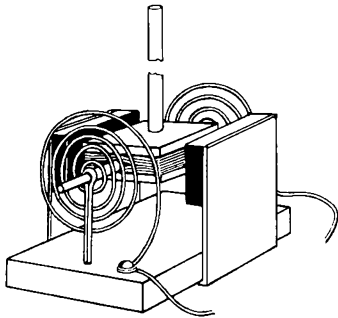


Fig. 114

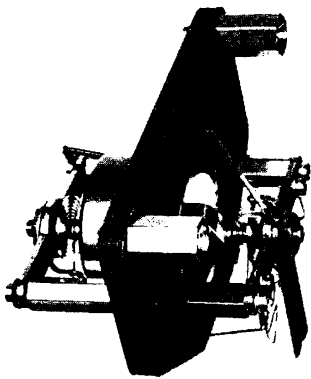


Fig. 115

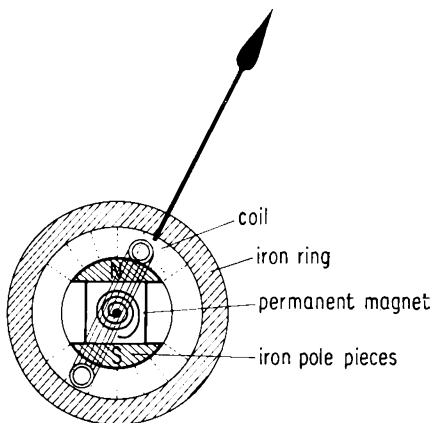


Fig. 116

Project 5.12. Start with the apparatus shown in Fig. 113 and see if you can improve it so that a pointer can be used to indicate the current flowing through the coil. How would you calibrate the instrument? Could it be used with a.c. and d.c.? Would it make a good voltmeter? Explain your answer clearly.

Moving Coil Meter

One of the defects of the simple galvanometer described in Experiment 5.11 is its dependence on the Earth's magnetic field. This is overcome in the moving coil meter, in which a coil of wire is free to rotate between the poles of a horse-shoe magnet.

Experiment 5.13. Use the Westminster electro-magnetic kit_{N92} to construct a simple moving coil ammeter (Fig. 114). A coil of 10 turns with about 4 turns on each 'spring' is adequate. A low voltage d.c. supply connected in series with a 15 ohm rheostat will allow you to alter the current through your ammeter. What is the greatest angle through which a coil like this can be made to turn by passing a current through it? Can this meter be used to measure a.c.? Explain your answers.

List the disadvantages of this primitive ammeter and say how they could be overcome.

A modern moving coil movement is illustrated in Figs. 115 and 116. Because of the radial field the deflection is proportional to the current in the coil.

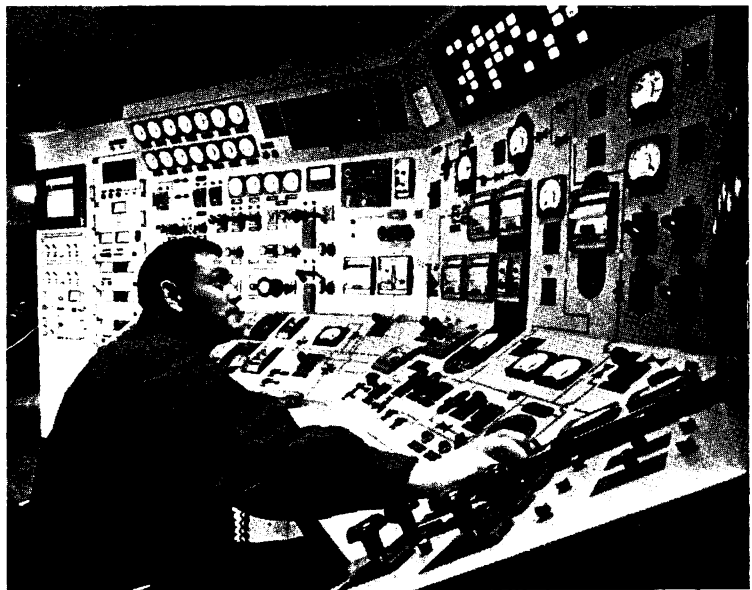


Fig. 117

Fig. 117 shows a number of moving coil meters used on the control panel of a nuclear power station in Antarctica.

Meter Constants

Every moving coil meter can be considered to have three *constants*. They are

- (i) full scale deflection (F.S.D.) current (I),
- (ii) full scale deflection (F.S.D.) voltage (V),
- (iii) resistance of the coil (R).

Why do we not state 'F.S.D. resistance' of the coil? (4). Will it be necessary to state all three constants on a moving coil meter? (5) How many need be stated? (6) Explain your answer. (7)

In the problems on meters it is often useful first to work out the particular 'meter constant' which is not given.

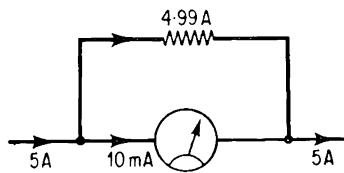


Fig. 118

Shunts and Multipliers

In order to use a moving coil meter to measure a large range of different currents and voltages, resistors may be added in parallel (shunts) or in series (bobbins or multipliers). *Should a good ammeter have a high or low resistance? (8) Why? (9) Fig. 118 shows a meter with a shunt fitted. Will the total resistance be greater or less than the meter resistance? (10)*

Ammeter

Example. A 0–10 mA moving coil meter reads full-scale when the voltage across its terminals is 100 mV.

$$\text{F.S.D. current } (I) = 10 \text{ mA}$$

$$\text{F.S.D. voltage } (V) = 100 \text{ mV}$$

How can this meter be used to read 0–5 ampere?

A shunt should be fitted to the meter as shown in Figs. 118 and 119. At full scale deflection the shunt will have to carry 4.99 A and the voltage across it will be the same as the voltage across the meter movement, that is, 0.1 V. The resistance of the shunt is therefore

$$R = \frac{V}{I} = \frac{0.1}{4.99}$$

$$= 0.02 \text{ ohms.}$$

How do you think a resistor of this value might be constructed? (11)

To check the reading of the meter, with its shunt attached, it could be connected in series with a standard 0–5 A meter. *If the reading on the meter under test was too high, would the resistance of the shunt be too great or too small? (12) How could this be altered? (13)*

Problem 14. What shunt would be required to adapt the above basic movement to read (a) 0–500 mA and (b) 0–10 A F.S.D.?

Problem 15. If a moving coil meter has a F.S.D. current of 1 mA and a resistance of 100 ohms, find its F.S.D. voltage. How could this meter be used to read (a) 0–1 A and (b) 0–25 A F.S.D.?

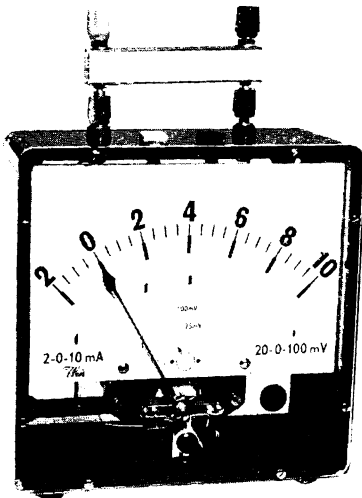


Fig. 119

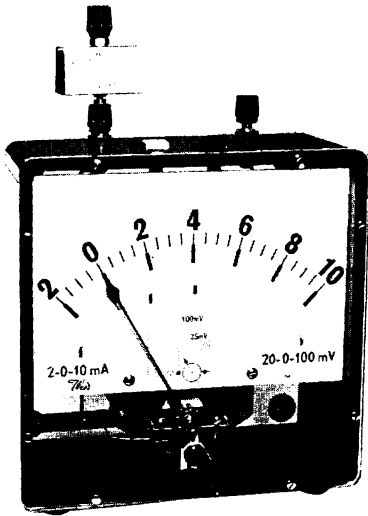


Fig. 120

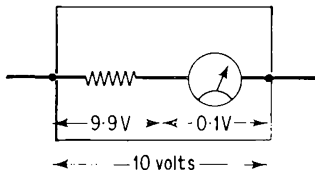


Fig. 121

Voltmeter

To convert a moving coil meter (F.S.D. = 10 mA, 100 mV) to a voltmeter which reads 0–10V a series resistor must be fitted (Figs. 120 and 121).

The bobbin or multiplier will have to drop 9.9 V and the current through it will be 10 mA at F.S.D. The resistance must therefore be

$$R = \frac{V}{I} = \frac{9.9\text{V}}{10\text{ mA}} = \frac{9.9}{10/1000} = 990\text{ ohms.}$$

If a resistance of 999 ohms were fitted, would the meter read high or low? (16) How would you check such a meter against a standard meter? (17)

Problems

18. (a) What series resistance would be needed to make the above movement into a 0–100V meter?

(b) How would you convert a 1 mA meter (resistance 100 ohms) into a voltmeter reading (i) 0–25V, (ii) 0–200 V F.S.D.?

19. A meter has a full scale deflection of 2 millivolts and a resistance of 50 ohms. How could it be used to read (a) 0–50V, (b) 0–5A F.S.D.?

20. Fig. 122 illustrates a simple multi-range meter. What would be the F.S.D. readings on ranges A, B, C and D?

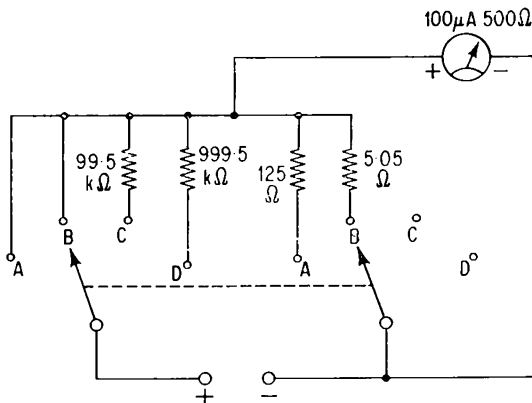


Fig. 122

21. A moving iron meter reads the potential difference across the terminals of a torch battery as 1.8 volts and a moving coil meter reads 2.6 volts. Why is this?

22. A multi-range voltmeter is marked '10 ohms per volt'.

(a) What will be its resistance on the 200V range?

(b) What would it read across an H.T. battery which has an e.m.f. of 120V and an internal resistance of 400 ohms?

(c) What would the same meter read on its 1000V range?

(d) If a meter marked '100 ohms per volt' were connected across the battery, what would be the reading on the 200V range?

Simple D.C. Motor

An electric motor is similar in principle to the moving coil meter you built earlier, except that the spiral springs are replaced by a commutator and brushes (cf. Book 2, pages 135 and 156f).

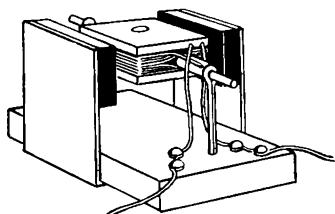


Fig. 123

Experiment 5.14. Attach the ends of a 10-turn coil to the commutator as shown in Fig. 123. In some kits_{N92} the commutator has to be constructed by first insulating the end of the aluminium tube with Sellotape, slipping two small rubber bands over this and fixing the ends of the wires under the rubber bands. The brushes are made by baring the ends of the supply leads.

Finally fix two magnadur magnets to the mild steel yoke to provide the field.

How can the motor be made to turn (i) faster, (ii) in the reverse direction?

Fig. 124 shows how you can use the ammeter built in Experiment 5.13 to give a rough indication of the current taken by this motor.

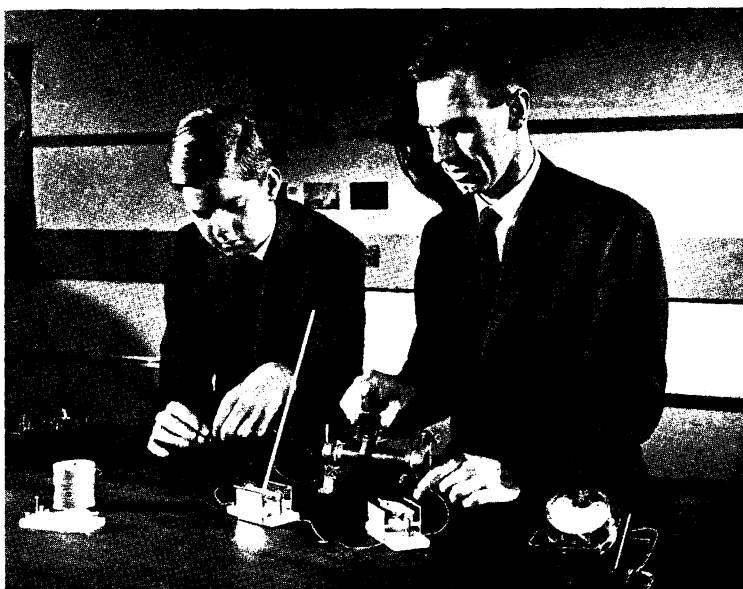


Fig. 124. From the Esso film 'The Electromagnetic Kit'

Experiment 5.15. Devise an experiment in which a small electric motor_{N9A} is used to raise a load. Find the time taken to raise the load and hence the output power of the motor in joules. How could you find the input power?

From your results calculate the efficiency of the motor. Is it the same when other loads are raised?

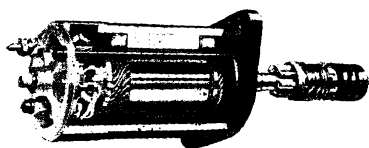


Fig. 125

Project 5.16. Examine a real electric motor such as the car starter motor illustrated in Fig. 125. Try to identify the armature, commutator, brushes and field windings. Why are there so many segments on the commutator? Why are the windings on a car starter motor made of copper strip rather than fine wire?

Practical Puzzle 23. Which household appliances use electric motors? Find out the power and current rating of each of these motors.

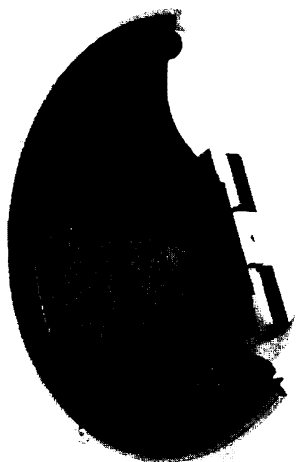


Fig. 126

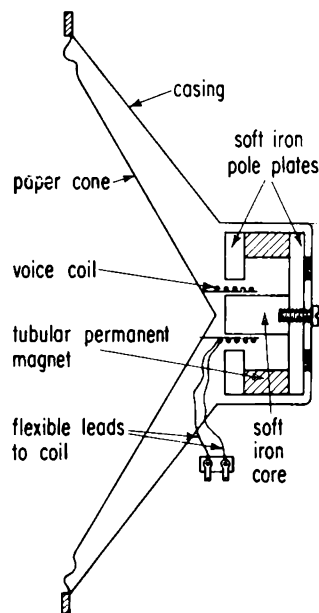


Fig. 127

Magnetic Effect Put to Work

Apart from meters and motors the magnetic effect of an electric current has many other useful applications. Can you explain how the ticker timer works? (24)

Figs. 126 and 127 illustrate the moving coil loudspeaker. The coil lies in a magnetic field produced by a powerful permanent magnet. When current flows in the coil the cone is pulled in or pushed out, depending on the direction of the current. With a current in the coil alternating at 1000 cycles per second how often will the cone vibrate to and fro every second?

Project 5.17. You can construct a model telephone earpiece from a large tin can and a C-core from the Westminster kit. Wind about 50 turns of wire on the core and attach the ends to the low impedance output of an oscillator or amplifier. Place a thin piece of foam plastic between the poles of the electromagnet and the end of the tin which acts as a diaphragm.

If a current alternating at 1000 cycles per second flows in the coil, how often will the ends of the tin vibrate to and fro every second?

Now place two magnadur magnets on the ends of the C-core so that the diaphragm is permanently attracted to the C-core (Fig. 128). Explain why the presence of the permanent magnet makes the diaphragm vibrate at the signal frequency. Both this model telephone and the moving coil loudspeaker may also be used as microphones.

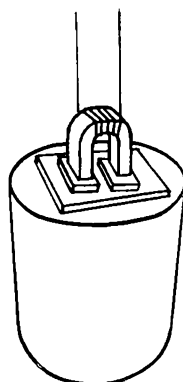


Fig. 128

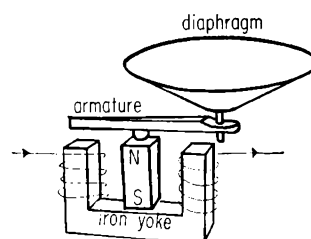


Fig. 129

A modern form of telephone earpiece, used by the G.P.O., is illustrated in Fig. 129. The armature pivots on top of the permanent magnet.

Project 5.18. Many electromagnets are used in a tape recorder. Can you discover the various uses to which they are put?

Problem 25. Relays depend on the magnetic effect of a current for their operation. Fig. 130 shows a circuit used in a car. Explain how it works and why a relay is necessary at all.

Problem 26. Draw a circuit in which a bimetallic strip (thermostat) and a relay are used to control an electric heating system. Why is the relay used?

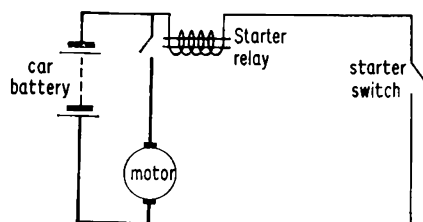


Fig. 130

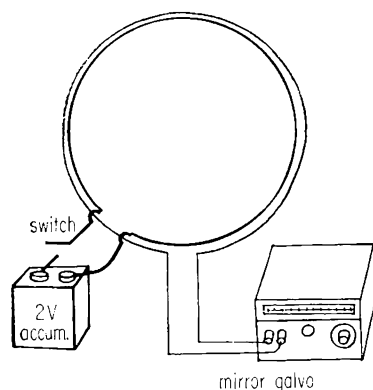


Fig. 131

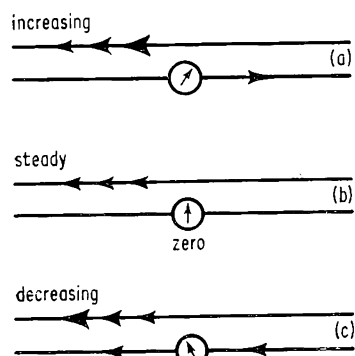


Fig. 132

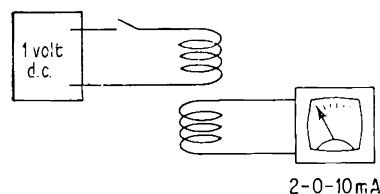


Fig. 133

Electromagnetic Induction

Demonstration 5.19. Take a 2 metre length of flat twin flex and connect the ends of one wire to a mirror galvanometer and the other to a 2 volt accumulator (Fig. 131). What happens

- when the accumulator circuit is completed?
- when a steady current is flowing in the accumulator wire?
- when the accumulator circuit is broken?

From the above experiment we see that, when the current in one circuit is *changing*, a current appears in the neighbouring circuit. This is called an *induced current*.

Considering the circuits illustrated in Fig. 132 we see that

- when the current in one wire is increasing (Fig. 132 (a)) there is an induced current in the other wire in the *opposite* direction;
- when the current in one wire is steady there is no current in the other wire (Fig. 132 (b));
- when the current in one wire is decreasing the induced current in the other wire is in the *same* direction (Fig. 132 (c)).

To remember the direction of the induced current imagine a car running on a farm track. If the car accelerates loose earth is thrown back and if it brakes suddenly the earth is carried forward with the car. If an electron *accelerates* in one wire it 'pushes' electrons in the other wire in the *opposite* direction. When an electron *decelerates* in one wire it 'pushes' electrons in the other wire in the *same* direction.

Experiment 5.20

(i) Connect a 10-turn coil to a low voltage d.c. supply such as the 1V output from the low voltage power unit. Attach a second 10-turn coil to a 2-0-10 mA meter and bring the two coils close together (Fig. 133). What happens when you switch on the power supply? What happens when you switch it off? Do not allow the current to flow for more than a second or two.

(ii) Repeat the above experiment with the coils wound on an iron bar and then on a C-core. Do you detect any difference?

(iii) Now wind the coils on two C-cores joined together as shown in Fig. 134. In this way there is a complete magnetic circuit. Repeat the experiment and note the result.

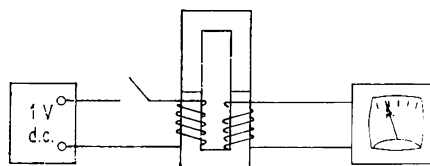


Fig. 134

(iv) What is the effect of the induced e.m.f. in the secondary if the number of turns in the secondary coil is increased?

Experiment 5.21. In this experiment an aluminium ring_{N92} is used as a 1 turn secondary.

Connect a 250-turn coil₁₀ to a 6 V d.c. supply. Suspend the aluminium ring on a thread and pass an iron bar through the ring and the coil as shown in Fig. 135. What happens to the ring (a) when the switch is closed, (b) when the switch is opened? Can you explain this behaviour in terms of the induced currents in the ring? Hint: use Fig. 132.

What would you expect to happen if a 6 V a.c. supply were used? Try it!

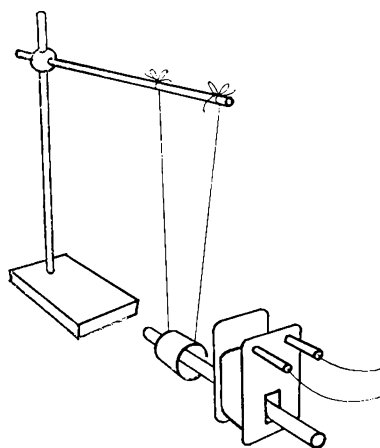


Fig. 135

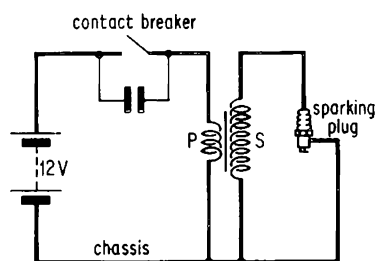


Fig. 136

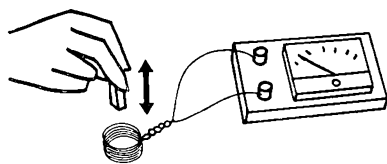


Fig. 137

Project 5.22

(i) Fig. 136 shows a car ignition circuit. You can construct such a circuit from an ignition coil and a sparking plug. The capacitor across the contact breaker reduces the arcing there and gives a better spark across the plug gap. Can you estimate the voltage across the plug? Explain how such a voltage is obtained.

(ii) Can you discover how an induction or shocking coil differs from an ignition coil?

(iii) An electric cattle fence also uses an induction coil. Try to find out how the contacts are operated.

Moving Magnets

The previous experiments have shown that an e.m.f. is induced in a circuit through which the magnetic field, due to a current, is changing. In the following experiments you should investigate the effects of relative movement between a permanent magnet and a conductor.

Experiment 5.23

(i) Plunge a bar magnet into a 10-turn coil of wire connected to a 2–10 mA galvanometer. Repeat the experiment (a) moving the magnet more slowly and (b) with more turns on the coil. Then complete the following statements.

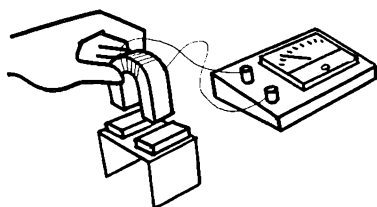


Fig. 138

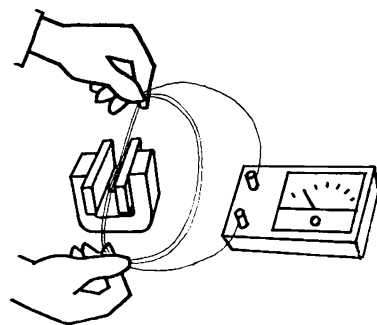
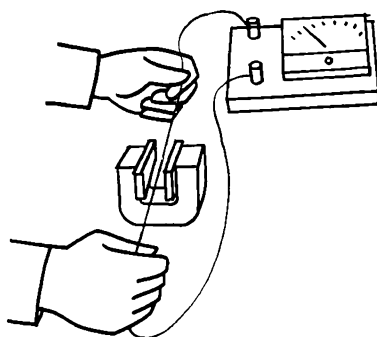


Fig. 139

When the rate of change of the magnetic field through the coil is increased the e.m.f. is . . .

When the number of turns in the changing field is increased the e.m.f. is . . .

(ii) Figs. 138 and 139 show other experiments with the electromagnetic kit. Use each to investigate the induced e.m.f. when a conductor moves in a magnetic field.

Demonstration 5.24. Use a 25-metre length of flex as a skipping rope, the ends of which are connected to a 2–0–2 mA galvanometer or similar instrument. Crank the wire in the playground with the axis (a) E–W and (b) N–S. Explain the results obtained.

Problems

27. Which of the following statements are true?

An e.m.f. is induced in a circuit

- (1) which is moving close to a fixed magnet,
- (2) when a magnet moves near it,
- (3) when a steady current flows in another circuit near it,
- (4) when a varying current flows in another circuit near it.

28. How is the induced e.m.f. affected by

- (a) increasing the magnetic field strength (B), for example by using a stronger magnet,
- (b) increasing the number of turns on a coil (l), and
- (c) increasing the speed at which the magnet and conductor move relative to one another (v)?

29. In what direction must the wire in Fig. 139 move between the magnetic poles to produce (a) the greatest, (b) the least induced e.m.f.?

Theory

If a wire is pushed down through a magnetic field from A to B as shown in Fig. 140, the electrons in the wire are moving, on the average, at right angles to the field lines. Successive positions of the wire are indicated. We have already seen that whenever electrons move across a magnetic field a *force* is exerted on them. This force on the electrons acts at right angles to the field (NS) and at right angles to the movement of the wire (AB). In Fig. 140 the electrons are pushed into the paper, that is, along the wire. The size of each cross represents the magnitude of the induced e.m.f. If this wire is part of a complete electrical circuit, a current will flow.

Project 5.25. You can construct a ribbon microphone from a thin strip of aluminium foil taken from a cigarette packet. Place the corrugated strip between the poles of a powerful horseshoe magnet, and connect the ends of the foil to the low impedance input of a sensitive amplifier. Explain the operation of the microphone (Fig. 141).

Demonstration 5.26

(i) Attach a 12,000-turn coil₂ to a C.R.O. (e.g. an S51E, preferably fitted with a long persistence tube). Demagnetise a hack-saw

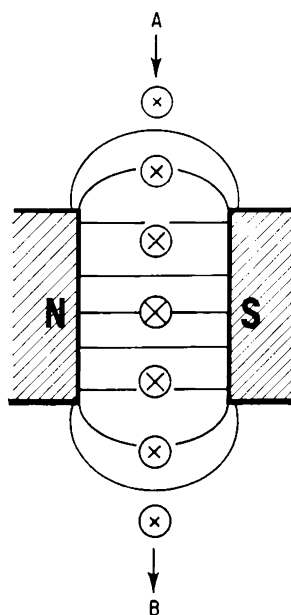


Fig. 140

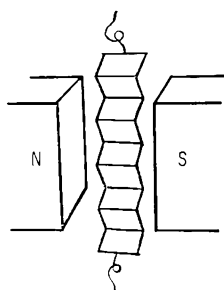


Fig. 141

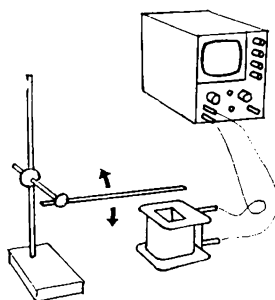


Fig. 142

blade and allow it to vibrate close to the coil (Fig. 142). Does the vibrating blade produce an e.m.f. in the coil?

Now insert a permanent magnet in the coil and see if it makes any difference. Can you explain why this should be?

(ii) Replace the coil with an electromagnetic earpiece and observe the results when the diaphragm is moved.

Project 5.27. Use two low impedance electromagnetic earpieces to construct a two-way telephone system. Each earpiece can be used both as a microphone and an earphone. Explain why this is so in terms of the results of the last experiment (Demonstration 5.26).

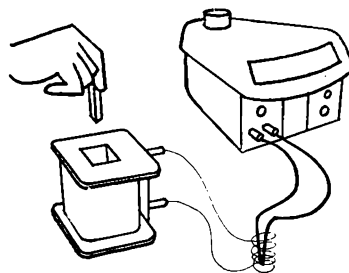


Fig. 143

Project 5.28. Construct a copper/constantan thermocouple and connect it to a mirror galvanometer or galvo-amplifier₉. Wind a small electrically insulated heater coil round the thermocouple and connect it to a 5000-turn coil₁₀. Now try to generate enough electricity to heat the junction by moving a bar magnet into and out of the coil (Fig. 143).

(Some very fine insulated wire, for example, 47 gauge, is suitable for the heater coil.)

Project 5.29. Allow a small ticonal magnet₉₂ to fall down a cardboard tube through a coil of wire. Feed the output of the coil to a C.R.O. with a long persistence tube. Explain the waveform obtained.

If a resistor is connected to the coil terminals, a current will flow when the magnet passes through the coil. Where does the energy come from? Will the acceleration of the magnet be altered as it passes through the coil? Why?

Dynamos

In 1819 Oersted showed that an electric current could produce a magnetic field. A few years later Michael Faraday began work on an attempt to produce the reverse effect, electric current from magnetism.

After many years of hard work, Faraday discovered the secret. The magnetic field had to be *changing* in order to induce a current in a nearby circuit. This discovery in 1831 was Faraday's crowning achievement. The electric generator or dynamo was born. In the following experiment you can use a simple electric motor as a generator.

Experiment 5.30. (i) Connect the leads from the commutator of a small electric motor (e.g. the one you constructed in Experiment 5.14) to a milliammeter and rotate the armature. Is the output a.c. or d.c.? How does the output vary when (a) the speed of rotation is increased, (b) the strength of the magnetic field is reduced?

(ii) Study the voltage produced when a rectangular coil is rotated between two magnets, for example magnetic pucks. A Russian-built motor₇ is used in the apparatus illustrated in Fig. 144. Other dynamos were described in Book 2, page 157f.

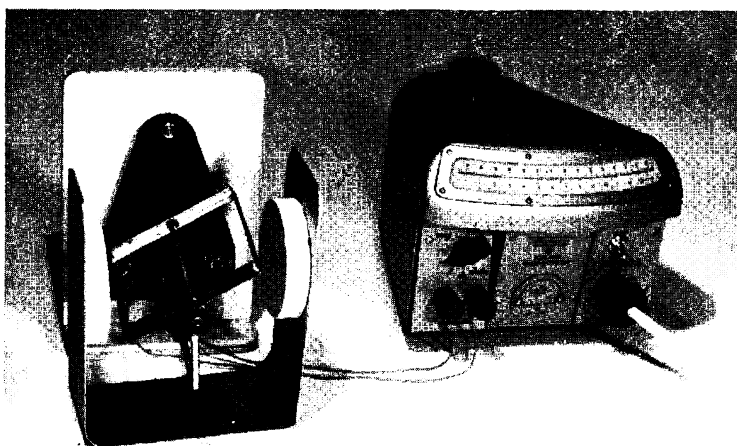


Fig. 144

Demonstration 5.31. Use a model steam engine_{N91} to drive a dynamo_{N9A} which is wired to a small torch bulb. What happens to the speed of the engine when the bulb is switched off? When current flows in the armature of the dynamo, a magnetic field is set up. Does this field oppose or assist the rotation?

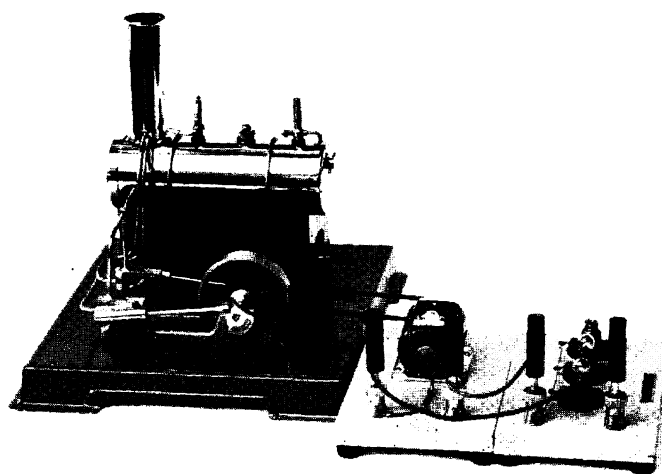


Fig. 145

Experiment 5.32. Connect a small electric motor_{N9A} to a battery, 0–1A meter and switch (Fig. 146). Note the current (i) when the switch is closed, (ii) when the motor is running freely at a constant speed and (iii) when the motor drives a load at a reduced speed. With a small motor the load can be provided by pressing on the shaft.

Explain the change in current in each case, remembering that the motor armature is revolving in a magnetic field.

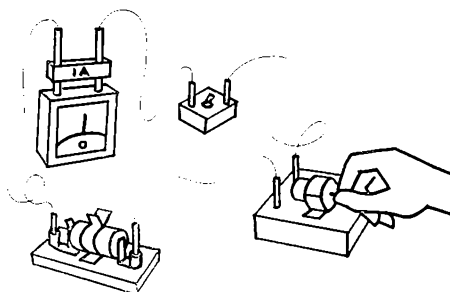


Fig. 146

Problem 30. Your young brother has just heard of *Ohm's Law* and proceeds to use it to calculate the current flowing through the armature of an electric motor. He divides the voltage of the battery by the resistance of the armature. Do you agree with him? If not, explain why you disagree.

Problem 31. If the brakes of an electric train failed, could the driver slow down the train 'electrically'?

Project 5.33. Devise an experiment to measure the power and efficiency of an electric motor (cf. Book III, page 104).

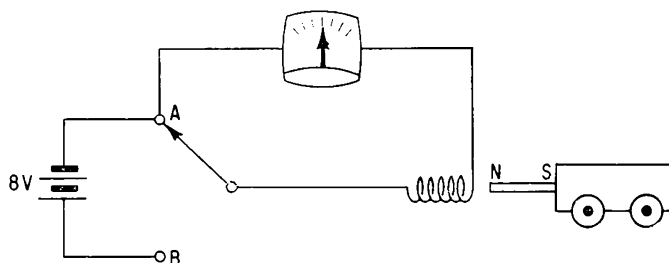


Fig. 147

Lenz's Law

Demonstration 5.34. Connect a coil of wire to a galvanometer and battery as shown in Fig. 147. Attach a bar magnet to a wagon which can run down a railway track and thus allow the magnet to enter the coil (Fig. 148). With the switch in position *A* push the wagon towards the coil. Note the *direction* of the current induced in the coil.

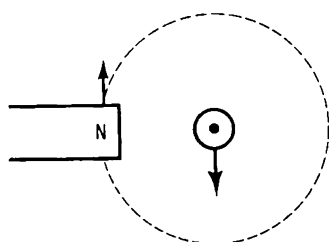


Fig. 149

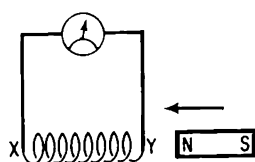


Fig. 150

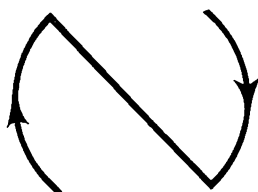


Fig. 151

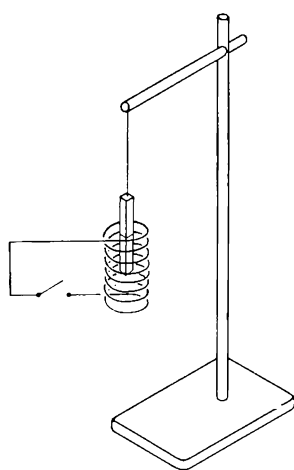


Fig. 152

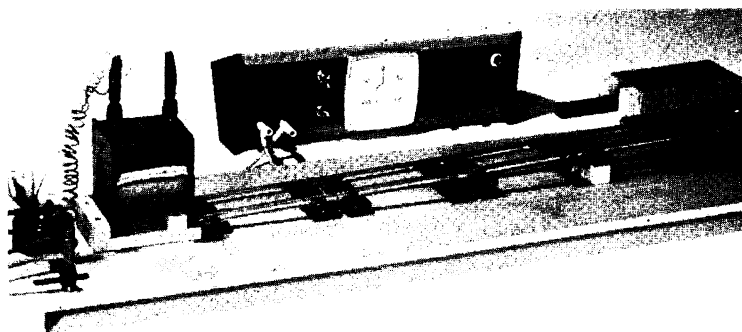


Fig. 148

Now switch to position *B* and arrange the battery so that it drives current through the coil in the *same* direction as before. If the magnet is inside the coil when the battery circuit is switched on, what happens? What does this tell you about the direction of the original *induced* current in the coil? Does the induced current tend to slow down or speed up the motion of the truck as it approaches the coil? Does the induced current oppose or assist the motion causing it?

(Suitable components are Galvoamplifier, with 30 cm of 26 gauge copper wire as a shunt, 300-turn coil_{N147}, 3 in. Eclipse bar magnet, two lengths of Hornby gauge 0 rail and a No. 50 waggon.)

Experiment 5.35

(a) Use the apparatus shown in Fig. 139 to discover the direction of the current induced in a wire pushed through a magnetic field. How can you discover the direction of the field lines experimentally?

Using the rule illustrated in Fig. 149, work out the direction of the force acting on the moving conductor due to this induced current for electrons coming out of the page. Does this force assist or oppose the motion of the conductor?

(b) Alternatively use a bar magnet and a coil (Fig. 150) and use the rule for a current-carrying solenoid. When electrons are moving clockwise round the coil you are looking at the north pole (Fig. 151). What are the induced poles *X* and *Y* when a magnet moves towards the coil? Does *Y* attract or repel the moving magnet? What happens to the induced current and poles when the magnet is pulled away from the coil? Is the magnet then attracted or repelled?

Lenz's Law is a statement of what you have discovered in these experiments. It states that ***the direction of an induced current is always such that it opposes the change causing it.***

What would happen if the induced *e.m.f.* were in the other direction? (32) Explain why Lenz's Law must be true if energy is to be conserved (33).

Experiment 5.36. Suspend two ticonal magnets, joined end to end, from a fine elastic thread. Allow the magnets to oscillate up and down in a 60-turn coil₁₀ (Fig. 152). Does short-circuiting the coil terminals make a difference to the oscillations? Why?

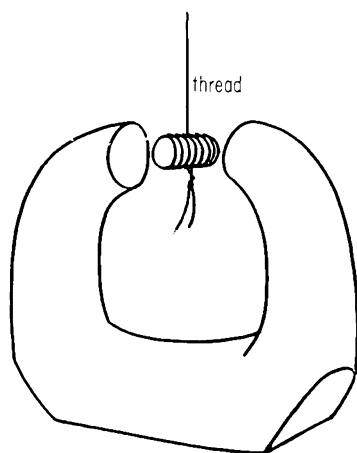


Fig. 153

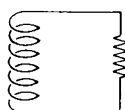


Fig. 154

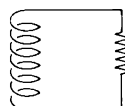


Fig. 155

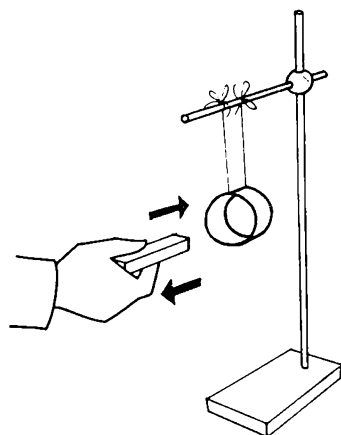


Fig. 156

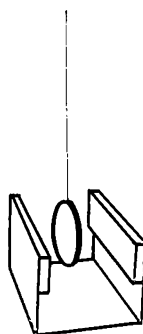


Fig. 157

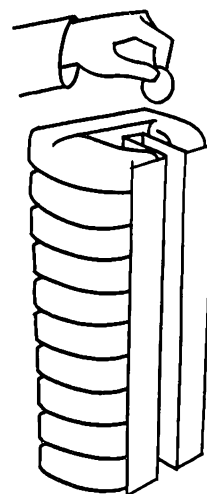


Fig. 158

Project 5.37. Wind a small coil of many turns on a cork and suspend it by a thread between the poles of a powerful horseshoe magnet (Fig. 153). Compare its rotation when the ends of the wire are on open circuit and then joined together. Explain your results.

Problem 34. Explain the result of Experiment 5.32 in terms of Lenz's Law.

Problem 35. Draw a few lines of force around each magnet and each coil in Fig. 154 and Fig. 155. What would be the effect of winding the coils clockwise instead of anti-clockwise as seen from above?

Eddy Currents

Experiment 5.38. Suspend an aluminium ring N_{92} on a thread as shown in Fig. 156. Move a ticonal magnet to and fro into the ring. What happens? Why? Why was an *aluminium* ring used? Would an iron ring give the same result? Explain your answer. If the magnet were suspended and the ring moved, what would happen? Test your answer by experiment.

Repeat the original experiment with a ring which has a gap in it. Explain the difference in the results obtained with this ring.

Experiment 5.39. The braking effect of eddy currents may be illustrated by other experiments as follows.

(a) A penny or aluminium ring is free to twist on a thread (Fig. 157). What happens when a horse-shoe magnet is brought up round the spinning penny?

(b) An aluminium disc may be dropped through a cardboard guide placed in the gaps of a number of horse-shoe magnets stacked on top of one another (Fig. 158). Why does it 'float' downwards?

(c) An aluminium disc is suspended on a number of threads so that it is free to spin in a horizontal plane. What happens when a bar magnet is brought close to such a spinning disc from below? Why?

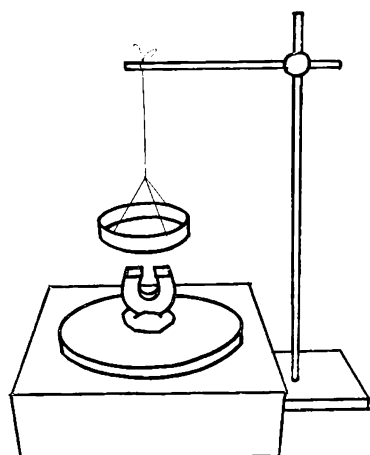


Fig. 159

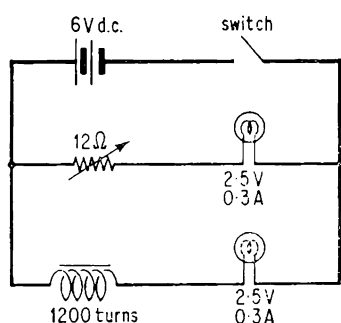


Fig. 160

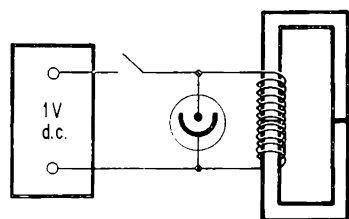


Fig. 161

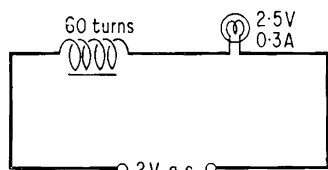


Fig. 162

If the disc is stationary and the magnet is then rotated on a gramophone turntable, what happens to the disc? (Fig. 159).

Can you think how such a device as this could be modified for use as a speedometer?

This experiment also illustrates the principle of the induction motor.

Practical Puzzle 36. Examine the coil of a moving coil meter. On what is the coil wound? Can you suggest a reason for this?

Inductance

We have seen that whenever a current *changes* in a circuit an opposing e.m.f. is induced in a nearby circuit. This *mutual induction* may be considered as follows.

1. There is a magnetic field associated with the current in the first circuit.
2. The strength of this field increases and decreases as the current increases and decreases.
3. The nearby circuit is therefore in a varying magnetic field.
4. The changing magnetic field induces an e.m.f. in this second circuit.

The original circuit is, however, also in a changing magnetic field, so that there is an induced e.m.f. in it as well. This e.m.f., called the *back e.m.f.*, opposes the change in the original current. This property is called self-induction or *inductance*. A coil, particularly a coil with an iron core or a large number of turns, has a large inductance. The coil is called an *inductor*.

Demonstration 5.40. In the circuit of Fig. 160 use a 1200 turn coil N_{147} on a core and a resistor, the value of which is such that when the switch has been closed for some time the bulbs are equally bright. Switch on and observe the bulbs. Which bulb lights up first? Can you explain the result in terms of inductance?

Repeat this experiment without the core in the coil. Does this make any difference? Why?

Experiment 5.41. Wind a 60-turn coil on two C-cores and connect a small neon lamp across it (Fig. 161). The neon requires about 70 volts to 'strike'. What happens when 1 volt d.c. is applied to the coil? What happens when the circuit is broken? Why? You can use this circuit to obtain an electric shock from a torch battery.

Inductors are used in this way to provide a big enough voltage to cause fluorescent tubes to strike.

(A 250-turn LB-3 coil I_{10} is also suitable for this experiment).

Problem 37. Why does arcing occur

- (a) at the contacts of an electric bell and
- (b) across the contacts in a car distributor? (Fig. 136)

Experiment 5.42. Use the 60-turn coil from Experiment 5.41 in series with a 2.5V 0.3A bulb and connect them to a 2V a.c. supply (Fig. 162). Switch on and observe the brightness of the bulb.

Repeat this experiment with the same length of wire but (i) half

the wire removed and then (ii) all the wire removed from the core. Explain the results in terms of inductance.

Can you suggest why such a coil is often used rather than a resistor to reduce alternating current through a circuit? As it cuts down or 'chokes' the current an inductor is sometimes called a 'choking coil' or, simply, a *choke*.

(A 250-turn LB-3 coil₁₀ is also suitable for this experiment.)

Optional Extras

Pick-up Coils

The fact that an e.m.f. is induced in a circuit which is in a changing magnetic field is used to feed information of various kinds into pick-up coils. One early gramophone pick-up consisted of a small coil between the poles of a permanent magnet. The needle was attached to a core inside the coil. As the needle moved to and fro in the groove of the record it caused the core to vibrate, thus changing the magnetic flux through the coil and causing small e.m.fs to be induced in the coil. These e.m.fs were then amplified.

Magnetic tape is used today to store information which is made available by running the magnetised tape close to a pick-up coil (see Book 2, page 85). Sound (audio) and vision (video) signals can be reproduced in this way. Fig. 163 shows a machine used to record television signals.



Fig. 163

Magnetic tape is also used to store information in computers (Fig. 164).



Fig. 165

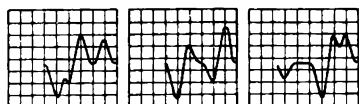


Fig. 166

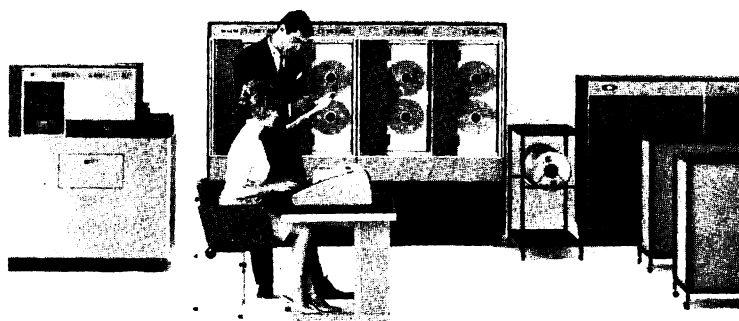


Fig. 164

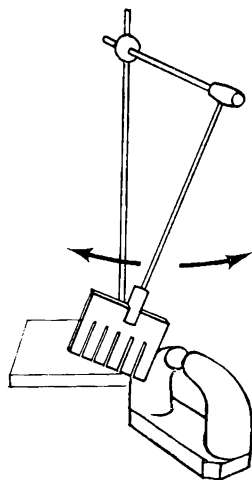


Fig. 167

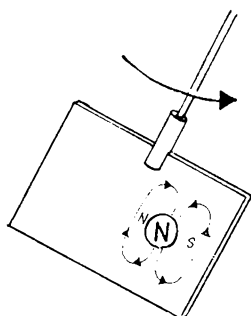


Fig. 168

Bank cheques are now sorted automatically by the use of an electromagnetic pick-up device. Each customer is given a number which is printed on his cheque in magnetic ink (Fig. 165). The numbers are then 'read' by passing them over a pick-up coil. Each character produces a different electrical waveform (Fig. 166), which enables the electronic sorter to file the cheques automatically.

Laminations

Experiment 5.43. Allow a solid metal pendulum bob, to swing freely and then to swing between the poles of a powerful magnet. Does the magnet affect the motion?

Repeat the experiment with a bob made of strips of metal separated from each other except at one end (Fig. 167). What difference do you observe? List some suitable and some unsuitable metals for the pendulum bob.

Consider a solid brass pendulum bob swinging between the poles of a magnet (Fig. 168). The red circle indicates the position of the near side pole (N). As the pendulum swings, e.m.f.s will be induced in it which will tend to cause currents to flow through other parts of the brass plate which are not in the field and in which there are therefore no induced e.m.f.s. Two possible paths are illustrated. If electrons flow in the direction indicated, the induced poles on the near side of the plate will be as shown in black ink. Do these induced poles tend to slow down or speed up the pendulum bob?

If the bob is laminated (Fig. 169), each lamination is in the *same* field most of the time and the laminations are not therefore short-circuited by a conductor which has no e.m.f. across it. The eddy currents are therefore very much smaller and the damping effect reduced.

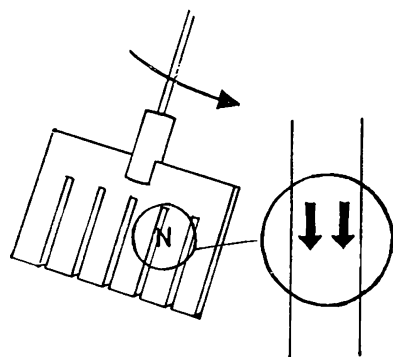


Fig. 169



Fig. 170

Additional Problem 38. A yacht with a steel mast sails on a straight course and cuts the Earth's magnetic field lines. An e.m.f. is thus induced between the ends of the mast. If now a meter is connected to the top and bottom of the mast as shown (Fig. 170), will a current flow through it? Explain your answer.

Summary

1. Currents in the same direction attract each other. Currents in opposite directions repel each other.

2. The force on a conductor increases with the current, the length of conductor in the field and the magnetic field strength.

Force $\uparrow \uparrow I, l, B$.

3. An e.m.f. is induced in a circuit which lies in a changing magnetic field. For a conductor moving at right angles to a field, the induced e.m.f. increases with the field strength, the length of the conductor in the field and the speed of the conductor.

Induced e.m.f. $\uparrow \uparrow B, l, v$.

4. Lenz's Law. The direction of an induced current is always such that it opposes the change causing it.

Visual Aids

Charts: Electromagnetic Induction₃₀ C892.

Filmstrips: History of Magnetism₃₅ E52.

8 mm Cassettes: Assembling the Electric Motor₁₉ 544.R14.

The Motor Effect₄₂ SP/E/8.

Electromagnetic Induction₄₂ SP/E/9.

Mutual Induction₄₂ SP/E/10.

16 mm Films: Michael Faraday 1791-1867₃₉.

Electromagnetic Induction₃₁ 2D.597.

Electricity and Movement₃₁ DF.573.

Electromagnets₃₁ 2D.2391.

Prelude to Power₃₁ 2D.2354.

Magnetism₃₁ 2DF.1103.

Magnetism₃₁ D.2565.

The Story of Magnetism₃₁ DC.2628.

Sound on Tape₃₆ 1359.106L.

The Magic Tape₃₆ 1380.250L.

Sound recording and reproduction₂₉ 20.7085.

The Electromagnetic Kit₃₇ (for teachers).

The Invisible Force₃₅.

Electrons in Space—Thermionics

CHAPTER 6

Escape Story

In an insulator such as cellulose acetate the electrons must be tightly bound to the atomic nuclei, since a great deal of energy is needed to remove them. You have already seen that some electrons can be removed from an acetate rod by rubbing it with a cloth. *With what net charge is the acetate left? (1) What kind of charge does the cloth have? (2)*

Even in conductors, where some of the electrons are not so tightly bound to the nuclei, electrons cannot normally escape from the metal 'of their own accord'. They seem to be free to roam around within the metal but not free to jump out of it. (See Book 2, Chapter 2.)

Under certain conditions electrons in a metal can, however, be released. A very strong electric field can drag some electrons from the surface of the metal (*field emission*) or they can be knocked out of the surface if it is bombarded by other electrons or ions (*secondary emission*). In the following experiments we will investigate two other ways of allowing electrons to escape from metals: *photo-electric emission* and *thermionic emission*. *What do the prefixes 'photo' and 'therm' suggest? (3)*

Photo-Electric Emission

Demonstration 6.1

(i) For this experiment an electroscope or electrometer with a clean zinc plate₁₁ is required. Charge the electrometer positively and then shine a bright light on the plate. What happens? Now bring an ultra-violet source₁₁ close to the plate. What happens? Record your results in the table below.

(ii) Repeat this experiment with the electrometer charged negatively.

(iii) Finally, note the effect of slipping an ultra-violet filter between the lamp and the zinc plate so that visible rays, but not ultra-violet rays, reach the plate. Record your results. What do they suggest?

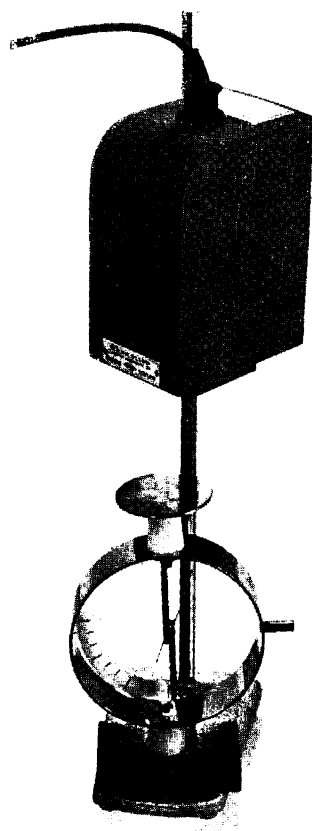


Fig. 171

	Ultra-violet rays	Visible rays
Plate positively charged		
Plate negatively charged		

The results of the above experiment can be explained by assuming that electromagnetic energy, such as light and ultra violet radiation, is transmitted in small quantities (or quanta)—each of a definite size. These 'particles of energy' or quanta are called *photons*. The approximate energies of photons in the visible spectrum are:

red	.	.	2.1 eV
green	.	.	2.7 eV
violet	.	.	3.4 eV

What trend can you see here in terms of energy and frequency? (4)

Electron volts (eV) are used to measure very small quantities of energy. $1 \text{ eV} = 1.6 \times 10^{-19}$ joules.

To release one electron from the surface of a metal requires a certain minimum amount of energy. In the case of zinc it is about 3.8 eV. A photon of visible light can never, therefore, provide enough energy to cause an electron to escape from the zinc. The energy in each quantum of ultra-violet radiation, however, is greater than 3.8 eV, so that when such radiation falls on a negatively charged zinc plate electrons escape and the charge on the plate is reduced.

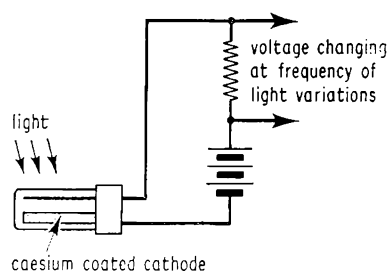


Fig. 172

Photo Cells

Only 1.9 eV is required to allow an electron to escape from caesium. This means that each photon of visible light has enough energy to release an electron from caesium.

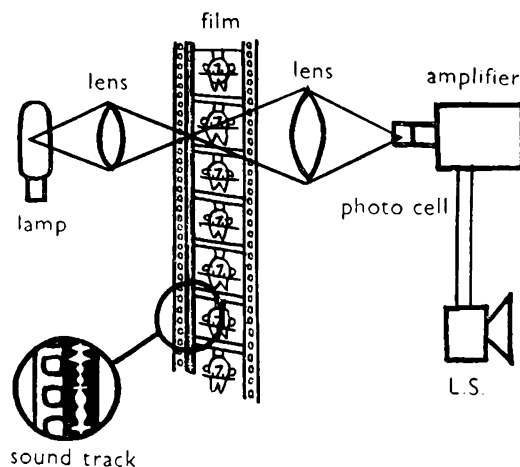


Fig. 173

In the type of photo cell used in a cine sound projector, light falls on a caesium coated cathode which then emits electrons. These electrons are attracted to a positively charged wire placed in front of the cathode so that a current, varying with the light intensity, flows through the circuit shown in Fig. 173. If the light first passes through the sound track of a film it will vary in intensity at the sound frequency, thus causing the photo cell current and the voltage across the resistor to vary at the same frequency. This voltage is then amplified and the output fed to loudspeakers (Fig. 173).

The photo-electric effect is also used in the tubes of some television cameras.

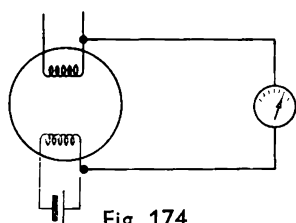


Fig. 174

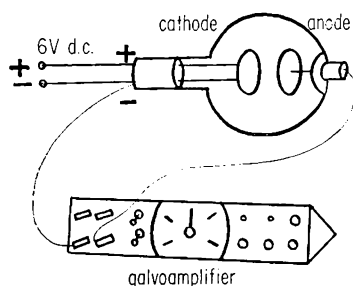


Fig. 175

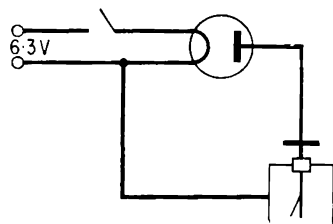


Fig. 176

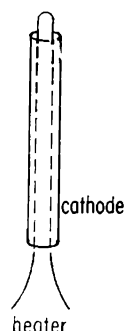


Fig. 177

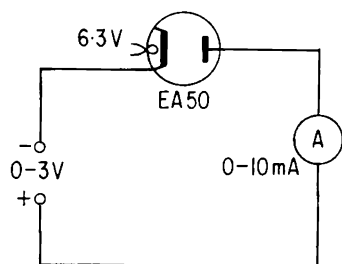


Fig. 178

Thermionic Emission

Among the 1300 patents taken out by the prolific American inventor Thomas Edison was one which led to the science of *electronics*. Edison had designed a light bulb with two filaments. When one filament burned out the bulb was turned round in its socket to connect the spare filament. One day as he was testing one of these bulbs he discovered that, if he connected a wire from the glowing filament to the spare filament, a small current flowed (Fig. 174). We can conduct a similar experiment.

Demonstration 6.2. Connect a sensitive galvanometer (e.g. a galvoamplifier) between the anode and the negative side of the cathode of a diode₁ (Tel 520 Fig. 175). What happens when the cathode is heated? Repeat this experiment with the galvanometer connected to the positive side of the cathode. What happens? Does the current in the external circuit flow in the same direction as before? Can you suggest a reason for this result? Originally called the 'Edison Effect', this phenomena is now referred to as *thermionic emission*.

This is hardly a practical way of generating electricity. Its efficiency is in the order of a few millionths of one per cent! The principle is, however, being developed in the hope of generating electric currents efficiently from nuclear energy. It is called *thermionic generation*.

The deflection of the galvanometer in the last experiment tells us that either negative charges are moving from the filament to the plate or positive charges are moving in the other direction. *Which do you think more likely?* (5) *Why?* (6) The following experiments will test your answers.

Demonstration 6.3

(a) Connect the case of an electroscope to the filament of a diode (Tel 520) and the electroscope plate to the anode (Fig. 176). How can you charge the electroscope plate etc. negatively? Do this and then switch on the filament. What happens?

Repeat the experiment with the electroscope plate charged positively. What happens? Why?

(b) Similar results were obtained using the Perrin tube (Book 2, page 29).

In commercial valves the cathode is often indirectly heated. It consists of an oxide-coated cylinder which is heated by a wire inside it. The heater is electrically insulated from the cathode.

Experiment 6.4. In the small EA50_{N156} diode the cathode is indirectly heated. Use 6.3V a.c. or d.c. for the heater, and with the circuit shown in Fig. 178 apply low voltages (up to about 3V) as shown. Note the current through the diode.

Reverse the battery connections and see what happens. Explain the results obtained.

Demonstration 6.5

(i) Connect a diode (Tel 520) to a milliammeter and d.c. supply as shown in Fig. 179. What happens when (a) switch 2 alone is closed, (b) both switches are closed?

(ii) Now reverse the connections to the H.T. supply and repeat the experiment. What happens? What do the results tell you?

(iii) How does the anode current vary if the d.c. supply voltage is reduced?

Fig. 180 shows a similar circuit. What do you think the meters are being used to measure?

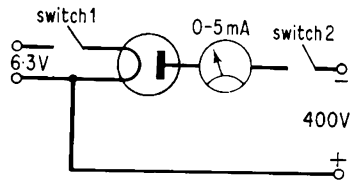


Fig. 179

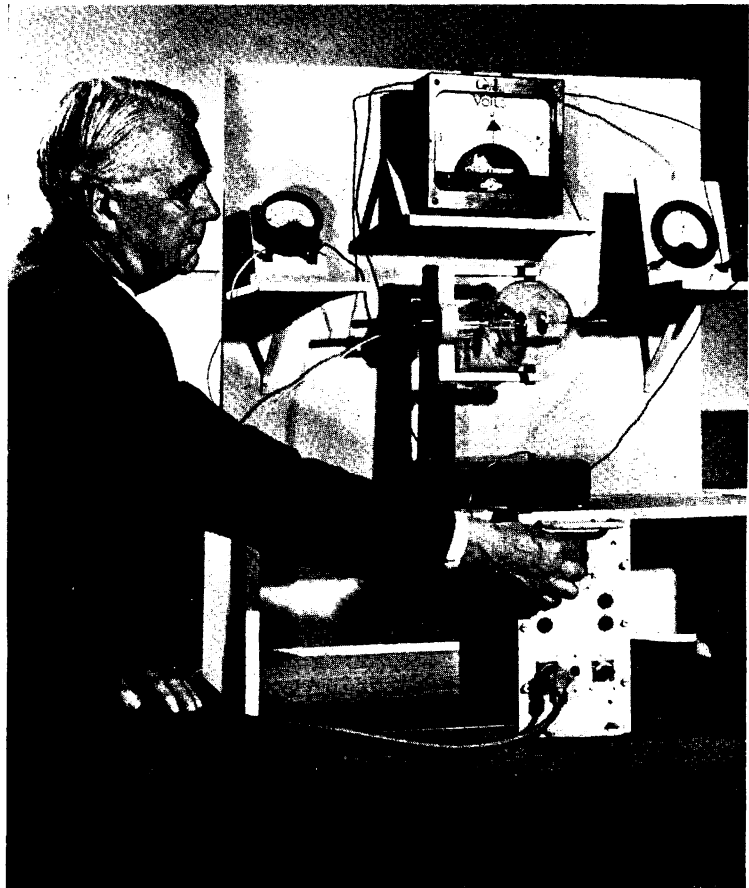


Fig. 180. From the Esso film 'An Approach to the Electron'

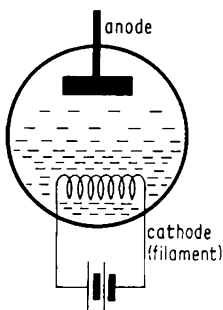


Fig. 181

Theory

When a liquid is heated to its boiling point some of the energetic molecules on the surface leave the liquid and fly off into the space above. The liquid changes to a vapour.

When a metal is heated to a very high temperature, as in the diode filament, electrons are given off. Some of the electrons in the metal must have escaped and flown off into the space around to form a 'space charge', that is, a 'cloud' of negative charges. *As these have come from the metal in the filament which was electrically neutral, what kind of charge must the filament now have? (7)*

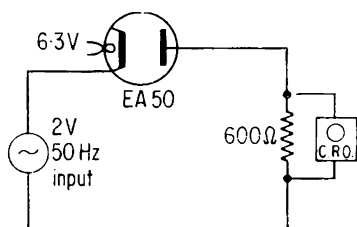


Fig. 182

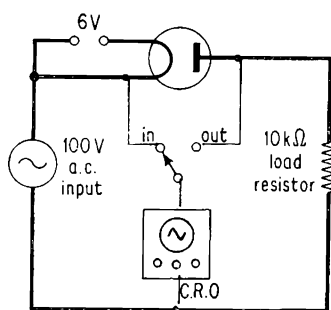


Fig. 183

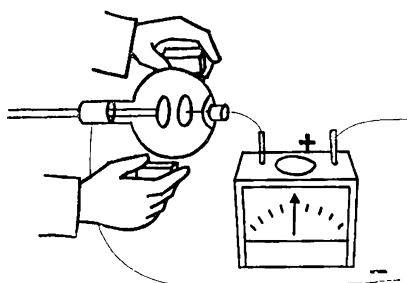


Fig. 184

If we simply heat a metal in air, the electrons in the space charge do not move very far from it. There are two possible reasons:

- (a) the air molecules around the metal collide with them;
- (b) the metal becomes more and more positively charged as more electrons leave it.

We can reduce the effects of (a) by placing the metal in a glass envelope and pumping out the air. This is exactly what is done in the diode valve. The electrons are, however, still attracted to the oppositely charged filament, although a few of the more energetic electrons reach the anode. If now a voltage is applied between the anode and the filament (the anode being positive), many of the electrons in the space charge are pulled across from the filament to the anode. This is the electric current indicated by the meter in the anode circuit.

When the anode is negative with respect to the filament, no current is observed, since the electrons are repelled from the negative anode. The diode is thus a 'one way street' for electrons and is often called a thermionic *valve*.

Rectification

One of the most common uses of a thermionic diode is illustrated in Fig. 182. Here the diode is used to allow electrons to flow through a resistor (load) in one direction although the supply is alternating current.

Experiment 6.6

- (i) Use an EA50 diode N_{156} in the circuit of Fig. 182 to investigate the waveform of the voltage across a 600 ohm resistor. Compare this with the input voltage.
- (ii) Connect various capacitors ($0.1 \mu\text{F}$ – $500 \mu\text{F}$) across the load resistor and note any change in the waveform.

Demonstration 6.7. This is an alternative to the above experiment.

- (i) Connect a diode d_1 in the circuit of Fig. 183. Use an oscilloscope to compare the input and output voltages and sketch the results.
- (ii) Connect across the load resistor the following capacitors in turn. $0.1 \mu\text{F}$, $1 \mu\text{F}$, $10 \mu\text{F}$, $100 \mu\text{F}$. Note any change in the output waveform.

Demonstration 6.8. Connect a 0–5 mA meter in the anode circuit of a diode (Tel 520). Hold two magnadur magnets on one side and another two at the other side of the tube (Fig. 184). Explain the change in anode current.

The Triode

In 1904 Ambrose Fleming used the Edison effect in the first practical diode valve. In trying to improve on Fleming's diode, Lee De Forest inserted an array of wires, in the shape of a grid-iron, between the filament and the plate. He discovered that the current through the valve could be varied by applying a voltage between this 'grid-iron array' (grid) and the filament.

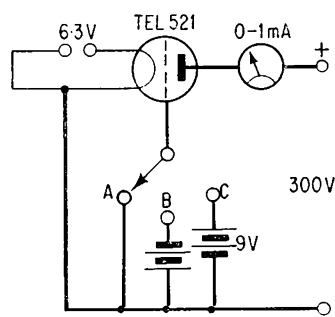


Fig. 185

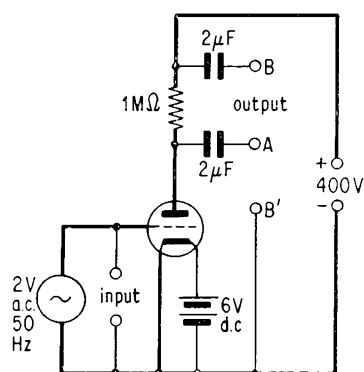


Fig. 186

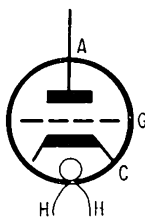


Fig. 187

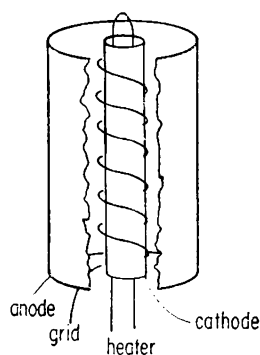


Fig. 188

Demonstration 6.9

(i) Using a triode (Tel 521) in the circuit of Fig. 185, note the current when the grid is (a) connected to the filament, (b) 0–9 volts negative with respect to the filament and (c) 0–9 volts positive with respect to the filament.

(ii) Place a voltmeter across the H.T. supply and note the *change* in anode voltage needed to *change* the anode current by the same amount as (say) a 6 volt change on the grid.

(iii) Is the anode current greater when the grid is connected to the filament or on open circuit? Why?

The Triode Amplifier

Demonstration 6.10. Apply about 2 volts a.c. (r.m.s.) between the grid and the cathode (filament) of a triode (Tel 521) as shown in Fig. 186. Connect a C.R.O. first to the input and then to the output terminals AB or AB'. What do you observe?

The $2\mu\text{F}$ capacitors allow only the alternating voltage to be applied to the oscilloscope.

Because of the change in anode current made possible by a small change in grid voltage, the triode can be used as a voltage amplifier. A *small* change in grid voltage can cause a *large* change in the voltage developed across a resistor in the anode circuit.

Suppose that in the circuit of Fig. 186 the H.T. is 400V and the steady anode current is $200\mu\text{A}$. The p.d. across the load resistor AB will be 200V ($V = IR = 200/10^6 \times 10^6$) and the p.d. across the valve AB' will be also 200V ($400 - 200$).

Now suppose that the anode current is made to alternate from $100\mu\text{A}$ to $300\mu\text{A}$ (i.e. $100\mu\text{A}$ up and down from the steady value) by applying an alternating voltage between the control grid and filament. The p.d. across the load resistor will alter between 100V and 300V , that is, by 100V up and down from the steady value. But because the H.T. supply voltage is fixed at 400V the voltage across the valve will vary between 300V and 100V , that is, 100V up and down from its steady value. So whether we consider the variations across the load or across the valve we get the same value for these variations. The a.c. output is therefore the same across AB and AB' but in practice it is the output across AB' which is normally used, as B' is at earth potential.

Commercial triodes are very different in construction from the model triode used in the last experiment. The simple wire filament is often replaced by an indirectly heated cathode. The grid is an open coil of wire wound round the cathode on a former and the anode consists of a nickel cylinder round them both (Fig. 188).

When the grid is negative with respect to the cathode (Fig. 189) the anode current is small. Electrons leaving the cathode tend to be repelled as they approach the grid, and only the more energetic electrons get through to the anode.

When the grid is positive with respect to the cathode (Fig. 191) a large anode current is produced. The electrons are accelerated and many more pass through the grid to the anode. Some are, however, attracted to the grid itself, so that grid current flows. In most practical circuits the grid is never allowed to become positive with respect to the cathode, so that no grid current flows.

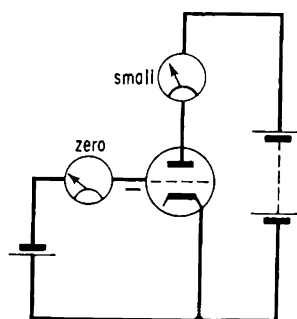


Fig. 189

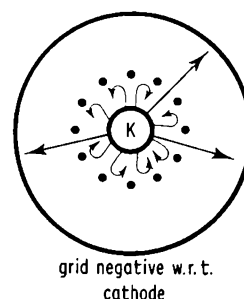


Fig. 190

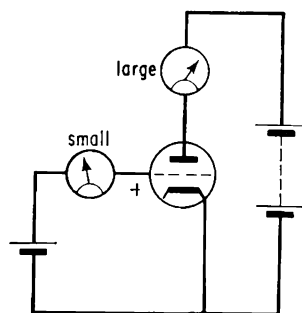


Fig. 191

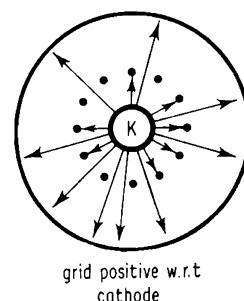


Fig. 192

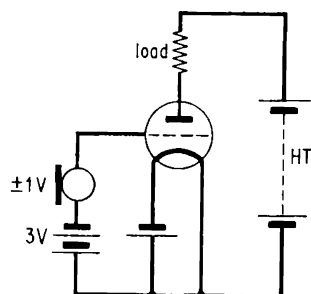


Fig. 193

Fig. 193 shows one way of preventing the grid becoming positive with respect to the cathode when an alternating voltage of (say) one volt is applied from a microphone. The 3 volt supply is called the grid bias.

Fig. 194 illustrates the use of a cathode resistor (R) to provide grid bias for an indirectly heated valve. If the anode current is 3 milliamps, what value of resistor would have to be used in the cathode to provide 3 volt grid bias? (8) A large smoothing capacitor is normally wired across this resistor so that a steady value of bias is provided. Why do we use the term 'smoothing'? (9)

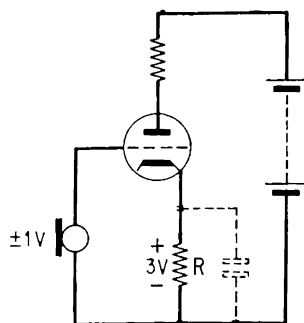


Fig. 194

Electron Gun

The picture on a TV tube is painted by a narrow beam of electrons striking fluorescent material on the inner surface of the tube. To produce the fine electron beam a device not unlike a triode valve is used. It is called an electron gun.

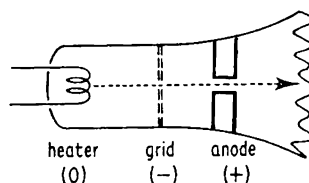


Fig. 195

Basically the electron gun consists of a heater which emits electrons, a grid to control the flow and an anode with a hole in it to allow electrons to pass through (Fig. 195).

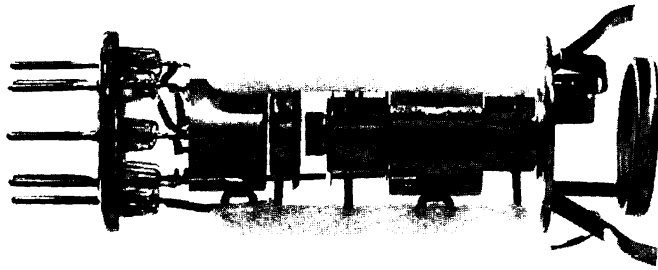


Fig. 196

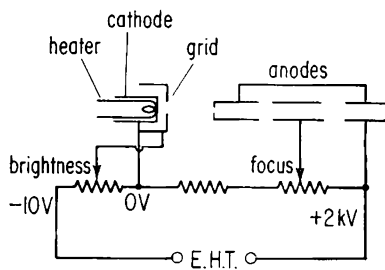


Fig. 197

In practice the gun may look more like Fig. 196. Electrons are emitted from an indirectly heated cathode which is surrounded by a cylinder—the control grid. Having passed through the hole at the end of the control grid the electrons enter a number of anodes which consist of cylinders at different potentials. By varying the potentials on one or more of the cylinders the electron beam can be *focused*. The grid voltage controls the *brightness* (Fig. 197).

C.R.O.

In a cathode ray oscilloscope and TV tube the electron beam is moved from side to side and top to bottom by an electric or magnetic field. You can study the effect of such fields on an electron beam in the next experiment.

Demonstration 6.11

(a) Using the circuit of Fig. 2 (a) and a Teltron tube 525, note the effect of making the upper plate positive and the lower plate negative with respect to the final anode of the electron gun. How does the deflection vary when the p.d. between the plates is increased? (In the case of the Teltron tube there is no control grid to vary the strength of the beam.)

Repeat the experiment with the plate supply reversed. If a magnetic field bends the beam upwards what is the direction of the field lines? Where would a permanent magnet have to be placed? Use a strong bar magnet to test your answer.

(b) The Leybold fine beam tube may be used to demonstrate similar effects (Fig. 3).

- (i) Use a bar magnet to study the movement of the electron beam.
- (ii) Pass a current through the Helmholtz coils and note the effect on the beam.
- (iii) Vary the H.T. voltage applied to the tube and note any difference. Will increasing the H.T. increase or reduce the kinetic energy of the electrons? Why?

In a cathode ray tube *two* sets of deflecting plates are used. The vertical deflecting plates (Y plates) are similar to those in the Teltron tube, and the horizontal deflecting plates (X plates) are set at

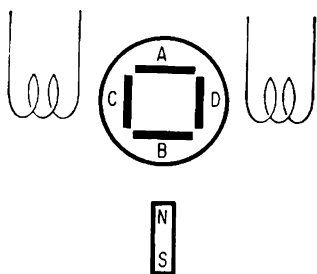


Fig. 205

(b) Connect a crystal microphone to the input terminals, and study the wave forms produced by a tuning fork, musical instrument and your own voice.

(iii) *Frequency measurement.*

Can you devise a way of measuring low frequency signals (say 10–300 cycles per second) from an oscillator? You should use the mains frequency to calibrate the C.R.O. More advanced types of oscilloscope have calibrated time base controls.

Problem 12. In Fig. 205 ABCD represent four deflecting plates in a cathode ray tube. Helmholtz coils are placed at the sides, and a bar magnet can be brought up to the position shown. How would the electron beam be deflected if the electrons were coming towards the reader and

- (i) A were made negative with respect to B,
- (ii) D were positive with respect to C,
- (iii) the bar magnet were brought up to the position shown,
- (iv) current in the coils produced lines of force from C to D?

Problem 13. What evidence is there for saying that electrons are (a) particles and (b) negatively charged?

Optional Extras

Television

A TV receiver is basically a modified form of C.R.O. which uses two time-base circuits instead of only one. The horizontal time base corresponds to that of the C.R.O. It moves the spot from left to right then returns it almost instantaneously to the left of the screen. At the same time a vertical time-base circuit gradually

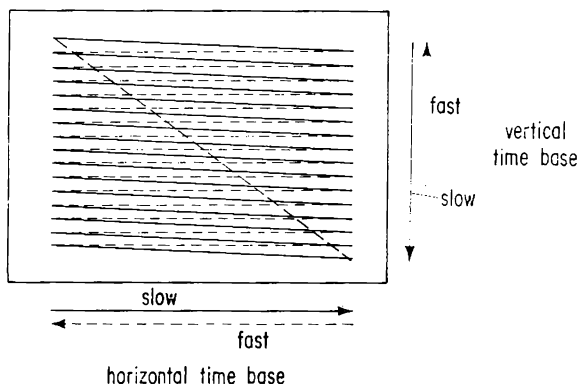


Fig. 206

moves the spot down the face of the tube and then returns it, again almost instantaneously, to the top (Fig. 206). In this way a number of lines of light, 405 or 625, is produced on the face of the tube.

To produce a picture from these lines of light, it is necessary to vary the intensity of the electron beam as it sweeps across the tube. The incoming signal does this by producing voltage changes between the control grid and the cathode of the TV tube. In this way

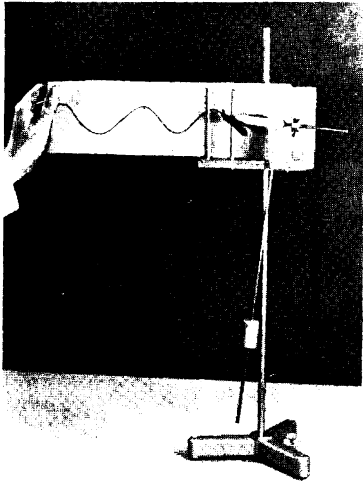


Fig. 203

time base frequency remained the same (50 cycles per second) and the input frequency was (a) reduced to 25 cycles per second, (b) increased to 200 cycles per second? (10)

Model 6.13. The model₂ illustrated in Fig. 203 shows how a sine curve may be produced from a to and fro movement (the pen) and a steady movement (the paper).

C.R.O. Controls

Brilliance

The strength of the electron beam is controlled by varying the voltage applied to the control grid.

Focus

By varying the voltages applied to the anodes of the electron gun the electron beam can be brought to a focus on the fluorescent screen.

Time Base Frequency

This control alters the frequency of the saw-tooth oscillator and thus the number of sweeps per second made by the electron beam. *What might this control adjust if the circuit of Fig. 201 was being used?* (11)

Amplitude

This is the gain control of an amplifier driving the Y plates.

X and Y Shift

These controls vary the no-signal voltages across the plates and enable the spot to be 'zeroed' at the centre or edge of the screen.

Uses of the C.R.O.

Oscilloscopes are now used in industry and research for so many purposes that it would be impossible to list them all. In the following experiment you can look at a few simple applications using a Serviscope Minor₁₂ or similar oscilloscope.

Experiment 6.14

(i) Voltage Measurement.

As the input circuit has a very, very high resistance practically no current is taken by an oscilloscope. It is therefore ideally suited for use as a voltmeter. Switch off the time-base circuit and adjust the X and Y shift controls so that the spot is central on the screen. Use a dry cell to apply 1.5 volts to the input terminals and adjust the amplitude control so that the spot is deflected 1.5 divisions on the scale. Now note the deflection when 3 and 4.5 volts are applied to the input. What is the effect of reversing the battery terminals?

Now apply 1 volt and then 2 volts a.c. from a low-voltage power pack. Worry about this for a wee while!

(ii) Wave-form Display.

(a) Use the C.R.O. to study the waveform from the low voltage power unit_{N104}, using first the a.c. output terminals and secondly the d.c. output terminals.

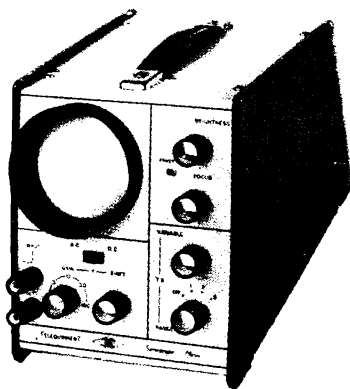


Fig. 204

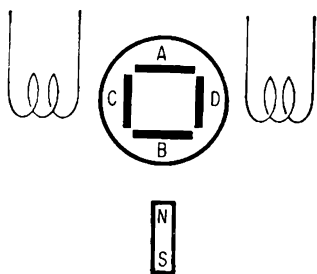


Fig. 205

(b) Connect a crystal microphone to the input terminals, and study the wave forms produced by a tuning fork, musical instrument and your own voice.

(iii) *Frequency measurement.*

Can you devise a way of measuring low frequency signals (say 10–300 cycles per second) from an oscillator? You should use the mains frequency to calibrate the C.R.O. More advanced types of oscilloscope have calibrated time base controls.

Problem 12. In Fig. 205 ABCD represent four deflecting plates in a cathode ray tube. Helmholtz coils are placed at the sides, and a bar magnet can be brought up to the position shown. How would the electron beam be deflected if the electrons were coming towards the reader and

- (i) A were made negative with respect to B,
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- (iv) current in the coils produced lines of force from C to D?

Problem 13. What evidence is there for saying that electrons are (a) particles and (b) negatively charged?

Optional Extras

Television

A TV receiver is basically a modified form of C.R.O. which uses two time-base circuits instead of only one. The horizontal time base corresponds to that of the C.R.O. It moves the spot from left to right then returns it almost instantaneously to the left of the screen. At the same time a vertical time-base circuit gradually

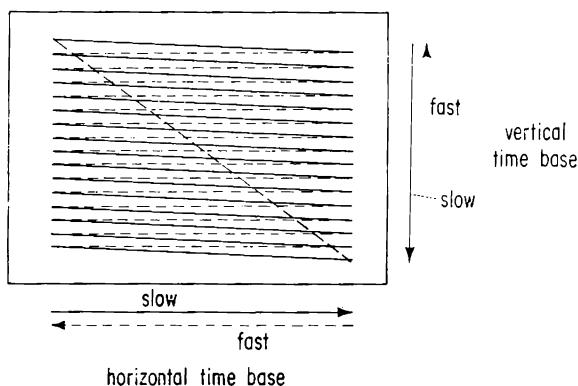


Fig. 206

moves the spot down the face of the tube and then returns it, again almost instantaneously, to the top (Fig. 206). In this way a number of lines of light, 405 or 625, is produced on the face of the tube.

To produce a picture from these lines of light, it is necessary to vary the intensity of the electron beam as it sweeps across the tube. The incoming signal does this by producing voltage changes between the control grid and the cathode of the TV tube. In this way

the brightness of the spot on the screen can be varied from black through a range of greys to white. Because we have persistence of vision, that is, because we continue to 'see' something for a small fraction of a second after it has disappeared, we recognise the conglomeration of black, white and grey as a complete picture. Twenty-five such (still) pictures are produced on a TV screen every second and if these are all slightly different an illusion of movement is observed. Movie pictures produce the illusion of motion in a similar way.

In addition to controlling the intensity of the electron beam, the incoming signal must be able to keep the time-base circuits in the receiver running in step with those in the TV camera (see page 94). This is achieved by transmitting a series of synchronizing pulses which are generated in the camera equipment. Finally, the TV signal must contain audio information which is fed to the loud-speaker in the TV set.

Project 6.15. Use a magnifying glass to study the structure of a newspaper photograph and then compare it with the structure of a TV picture.

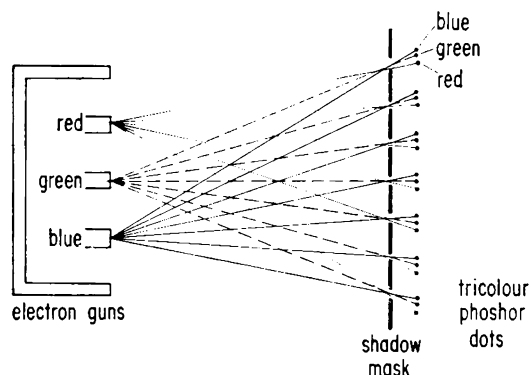


Fig. 207

Colour TV

A complete range of colours can be obtained from the three primary colours, red, green and blue (see Book 2, page 105). To obtain a colour TV picture, each 'dot' on the screen must therefore be able to emit varying intensities of each of these colours and not simply varying intensities of white light as are emitted by a conventional tube.

The phosphor screen in a colour tube contains nearly half a million triangular 'dots', each made up of one red, one green and one blue light-emitting crystal. The light emitted by these crystals is controlled by three electron beams, one for each colour.

To ensure that each beam is directed to only one type of crystal a perforated metal plate or *shadow mask* is placed behind the phosphor screen. Each hole in the mask is carefully aligned with the tri-colour dots so that one electron beam produces light of only one colour (Fig. 207).

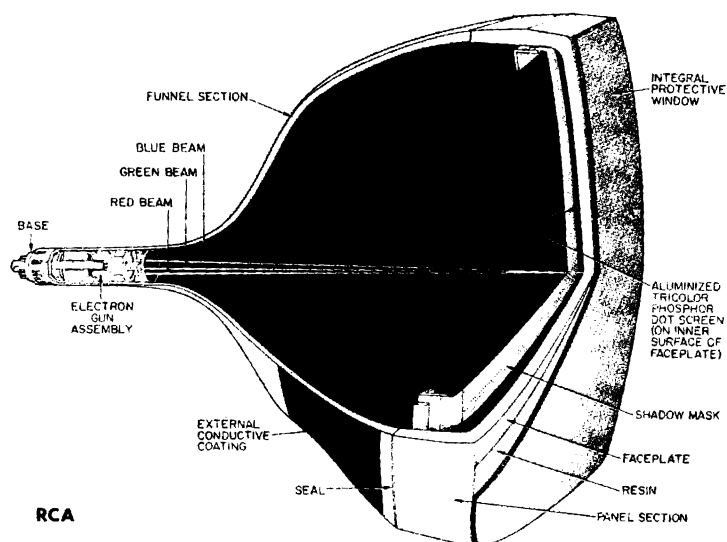


Fig. 208

As in the case of most black and white TV tubes, the deflection of the electron beam is controlled by varying magnetic fields. These are produced by coils placed round the neck of the tube. They are not shown in the diagram.

In a colour TV camera the light is split into three parts and then passed through a red, green or blue filter before entering the camera tubes (Fig. 209, top). The electrical signals are then combined to form a *brightness signal* and an additional signal which carries the colour information (dotted area).

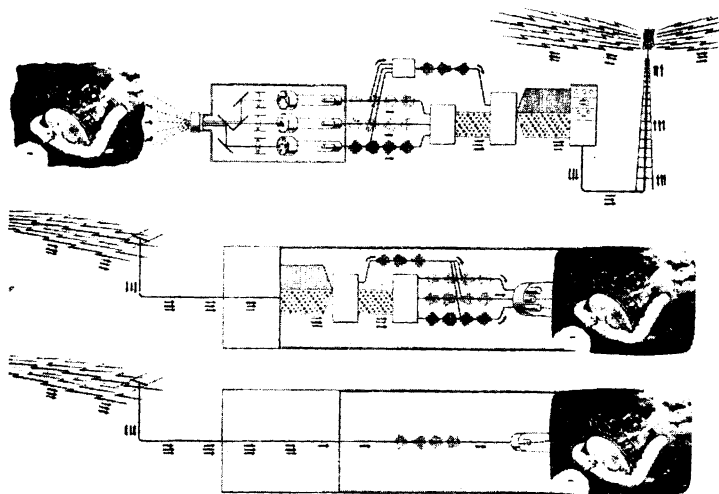


Fig. 209

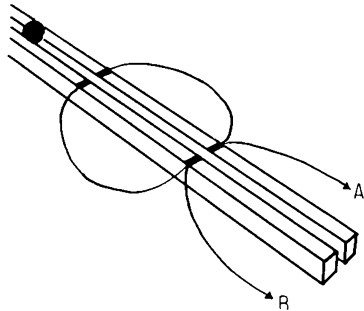


Fig. 210

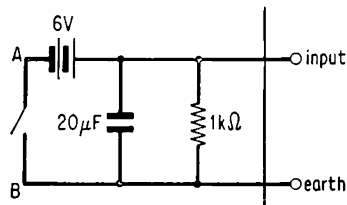


Fig. 211

The centre diagram shows how these signals are fed into a domestic TV receiver, and the bottom diagram shows how the brightness signal alone may be used on a standard black and white receiver.

Measuring Short Time Intervals

Demonstration 6.16. The S51E oscilloscope with a long persistence tube is suitable for this experiment. The circuit shown in Fig. 211 can be used to find the time taken for a ball bearing to run between two pairs of contacts on an inclined plane. If the ball completes a circuit each time it runs over a pair of contacts (Fig. 210), the time interval can be found by measuring the separation of two blips on the screen.

(The X gain must be at zero for the calibration to be valid. One volt/centimetre is a suitable setting for the Y amplifier. Stability and trig level controls should be adjusted until the trace begins when the control AB is closed momentarily. A second pulse is produced when the contacts are closed again. The capacity and resistance values given are suitable for use on the 100 ms range.)

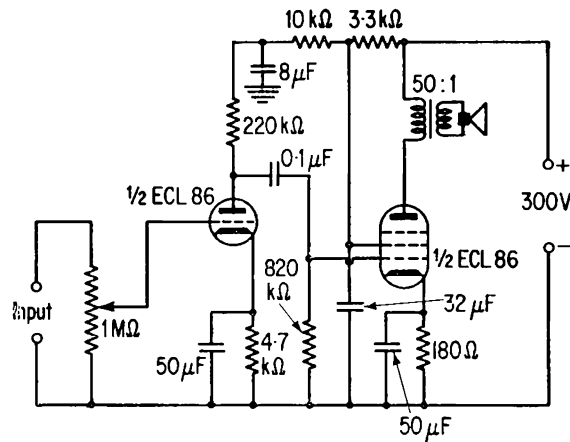


Fig. 212

Record Player Amplifier

Project 6.17. Fig. 212 shows a circuit for a two stage audio amplifier which you may like to build. Both valves are in one envelope and the gain is adequate for use with a crystal pick-up. A more advanced version fitted with base and treble controls and negative feed back is described in 'Mullard Circuits for Audio Amplifiers.'

Additional Problems

Problem 14. When an electron is accelerated across a p.d. of V volts it gains V electron-volts of kinetic energy. Taking 1 eV as 1.6×10^{-19} joules and the mass of an electron as 9×10^{-31} kg, find the speed of an electron when it reaches the anode of a valve on which the positive voltage is 500 V with respect to the cathode.

Can you suggest into what form this kinetic energy is largely transformed? How would this affect the construction of very large valves such as those used in transmitting stations?

Problem 15. A cathode emits 1.8×10^{17} electrons per second when hot. When 400 volts is applied to the anode the valve is saturated, that is, the maximum current is being passed through it.

(i) What is the anode current? (Charge on the electron is 1.6×10^{-19} coulombs.)

(ii) If all the kinetic energy of the electrons is changed to heat at the anode, what is the rate at which heat must leave the anode (i.e. what is the power) when a steady state is reached?

Visual Aids

Charts: Principles of Radio. 1. Amplification₃₀.

How Television Works₃₀ C744.

The Television Picture Tube₃₅.

The History of Television₃₅ E51.

Filmstrips: Electric Current in Gases and Vacuum₃₀ 5152.

The Diode₃₃ E101.

The Triode Valve₃₀ SS45.

Principles of Cathode Ray Tube₃₃ E.6.

Cathode Ray Oscilloscope₂₉ 08.0005.

Television Picture Tube₃₃ E105.

Introduction to Colour Television₃₃ E61.

8 mm Cassettes: The Diode Valve₃₄.

The Triode Valve₃₄.

The Triode as an Amplifier₃₄.

16 mm Films: Putting Free Electrons to Work₃₁ DF.576.

Cathode Ray Oscillograph₂₉ 20.2530.

How Television Works₂₉ 20.4732.

An Approach to the Electron₃₇ (for teachers).

Electrons in Semiconductors—Transistors

CHAPTER 7

Conductivity

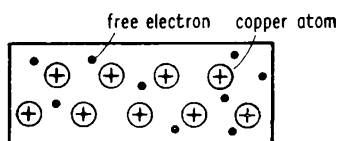


Fig. 213

Conductors such as copper contain some electrons which are not tightly bound to the nuclei of the atoms. These are referred to as free electrons (Fig. 213). A conductor is not, however, negatively charged, as there is normally an equal number of positively charged particles (protons) in the atomic nuclei.

When a p.d. is applied to the ends of the conductor, the electric field thus set up causes these free electrons to drift towards the positive terminal; that is, an electric current is produced.

No current will flow, however, when a p.d. is applied to an insulator unless the electric field is very strong, in which case some electrons may be pulled out of the atoms. In insulators the electrons are tightly bound to the nuclei of the atoms, and it is difficult for an electron to move from one atom to another.

The resistance between the opposite faces of a one centimetre cube of material is called the electrical *resistivity* or specific resistance. It may be 10^{-6} ohms for a good conductor at normal temperatures and as much as 10^{18} ohms for a good insulator. Somewhere between conductors and insulators lies a group of materials called semiconductors; they include germanium, silicon and selenium. The table gives approximate values for the resistivity of various materials at 0°C .

Electrical resistivities at 0°C in microhm-centimetre

Aluminium	2.5	Lead	19
Arsenic	32	Magnesium	3.9
Ceramics	10^{20}	Mercury	94
Constantan	49	Polythene	10^{24}
Copper	1.6	Paraffin wax	10^{22}
Germanium	$\sim 10^5$	Selenium	$\sim 10^7$
Glass	10^{18}	Silicon	10^3 – 10^6
Gold	2.0	Silver	1.5
Graphite	10^3	Tungsten	4.9
Indium	8.0	Zinc	5.5
Iron	8.9		

The resistance between the opposite faces of a one centimetre cube of semiconducting material might range from about one ohm to over a million ohms. An important difference between a semiconductor and other materials is that its resistance can be made to change quite drastically by various means.

In 1833 Michael Faraday discovered that the resistance of silver sulphide increased when it was cooled down. He thus made one of the first important contributions to the study of semiconductors.

Experiment 7.1

(a) Connect a piece of germanium₂ in series with a 6 V 0.06 A torch bulb and 8 V supply. Heat the germanium in a beaker of water and note the result obtained. What happens to the resistance of the germanium as the temperature rises?

(b) Investigate the change of resistance of a TH3 thermistor₁₄ when it is heated. Alternatively heat an OC71 transistor in a beaker of oil, noting the change of resistance between the emitter (+) and the collector (—).

Experiment 7.2. Investigate the change of resistance of an ORP12 cadmium sulphide cell₁₃ when light falls on it. Alternatively a photo transistor may be used (cf. Book 2, page 111).

These experiments show that heat and light have a marked effect on the resistance of semiconductors. Many of the electrons which, at low temperatures, are tightly bound in the crystal lattice of the semiconductor are given sufficient energy from the heat or light to enable them to break away from the atoms. These free electrons are then available as charge carriers and so the resistance of the materials falls.

The operation of one type of television camera—the Vidicon—depends on the change in the resistance of a semiconductor when light falls on it. The Vidicon consists of a cathode ray tube in which the fluorescent screen is replaced by a semiconductor disc. On the front surface of the disc there is a transparent conducting layer which is wired to an external circuit (Fig. 214). In total darkness the resistance of the semiconductor is very high, so that very

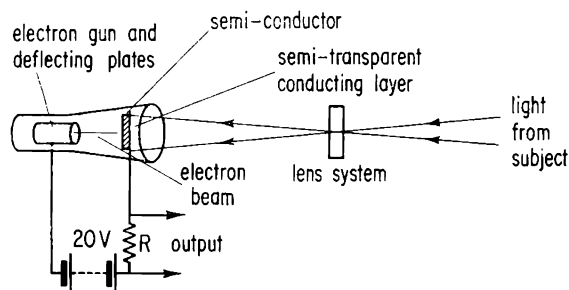


Fig. 214

few electrons pass through the semiconductor to the conducting layer. The current in the external circuit is therefore small and the voltage across R negligible. When light falls on the front of the tube it passes through the conducting layer to the semiconductor, reducing its resistance and allowing the electrons to pass from the beam to the conducting layer. Current now flows in the external circuit and a voltage is developed across the load resistor R . The output voltage then depends on the amount of light falling on the end of the Vidicon tube.

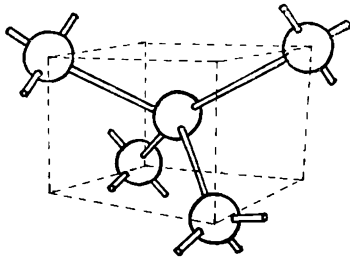


Fig. 215

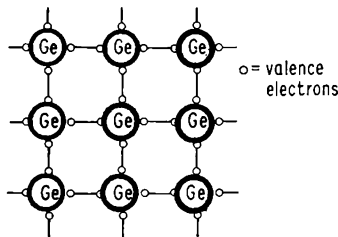


Fig. 216

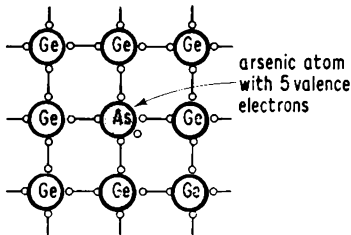


Fig. 217

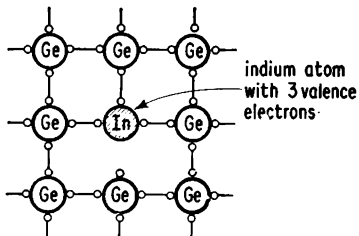


Fig. 218

If now a lens system is used to focus a picture on the tube and if at the same time the electron beam is made to scan across the semiconductor, as in a TV receiver, the output voltage will vary with the brightness of the picture area being scanned.

Germanium

The element germanium was discovered in 1886. It is a hard and brittle silver/grey substance. Its atoms are arranged in a tetrahedral lattice so that each of the four valence electrons is linked to an adjacent atom, forming a 'shared electron' covalent bond. Fig. 216 shows a two-dimensional representation of the three-dimensional crystal structure of Fig. 215.

At very low temperatures the material behaves like an insulator, since there are very few free electrons. As the temperature of germanium rises the resistance decreases as more and more electrons break away from the lattice.

In addition to the action of heat and light on a semiconductor such as germanium, charge carriers can be made available by introducing a trace of another substance into a pure crystal lattice. This impurity may be only one part in a hundred million, but as there are about 10^{22} atoms per cubic centimetre in a germanium crystal this still leaves 10^{14} atoms of impurity in each cubic centimetre of the semiconductor. This trace of impurity can reduce the resistivity of the germanium to less than one tenth of its original value.

n-type Germanium

A few atoms of arsenic may be introduced as an impurity into germanium (Fig. 217). An arsenic atom has five valence electrons, so that, as only four are required for the process of bonding, one free electron becomes available as a charge carrier. The germanium is now called *n-type* germanium as it has negative charge carriers (electrons) donated by the impurity. Notice that n-type germanium is not negatively charged any more than is a piece of copper wire. For every free electron, there is a proton in an arsenic nucleus; n-type germanium is therefore electrically neutral.

p-type Germanium

If a few atoms of indium are added to pure germanium, the situation is quite different (Fig. 218). Indium has only three valence electrons, so that an electron is now needed to complete the lattice. If one electron should be released from a germanium atom by thermal energy, the indium atom will immediately grab it! The vacancy left is referred to as a *hole*. Whenever an electron fills the hole, another hole is formed somewhere else in the germanium, so that *in effect* holes are moving through the germanium. As each hole represents the absence of an electron, this 'migration of holes' can be thought of as a movement of positive charge carriers. The material is therefore called *p-type* germanium. Notice again that p-type germanium is not positively charged. There is exactly the same number of protons within each indium nucleus as

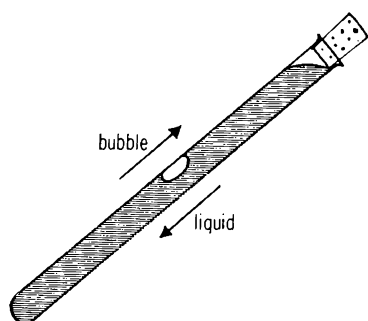


Fig. 219

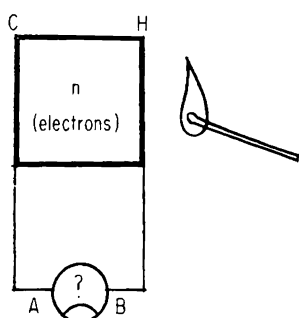


Fig. 220

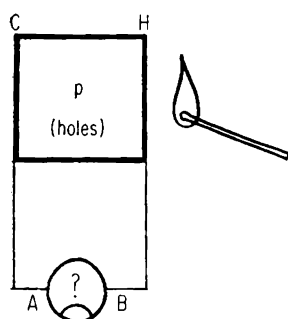


Fig. 221

there are electrons around it; p-type germanium is therefore electrically neutral.

When a bubble runs up a tube of liquid, we think of the bubble moving *up* rather than the liquid running *down*. We could say that a hole was moving up the tube. In semiconductors it is easier to think of the movement of holes (positive charge carriers) in p-type materials and of electrons (negative charge carriers) in n-type materials.

Demonstration 7.3

(i) Connect the ends of a piece of n-type germanium₁₀ to a sensitive meter as shown in Fig. 220. Heat one end of the germanium and from the deflection of the meter determine the direction in which (a) positive and/or (b) negative charges move through the n-type germanium. If the charge was carried mainly by electrons, in which direction would they move?

(ii) Repeat this experiment with p-type germanium (Fig. 221). If the charge was carried mainly by holes, in which direction would they move?

The above experiment shows clearly that there is a difference in the behaviour of the two types of germanium. We might predict, by analogy with gas molecules, that the charge carriers present are more likely to move away from the hot end of the germanium slab. If this is so, the carriers in the n-type germanium must be electrons and those in the p-type germanium must be positive holes.

The Hall Effect

Before looking at the Hall Effect itself let us look at a model which illustrates a similar effect.

Model 7.4. Connect a Teltron 525 tube to an E.H.T. supply and a mirror galvanometer as shown in Fig. 222. When the supplies are switched on an electron beam will pass between the plates, but there will be no deflection in the galvanometer. This shows that there is no voltage between the plates.

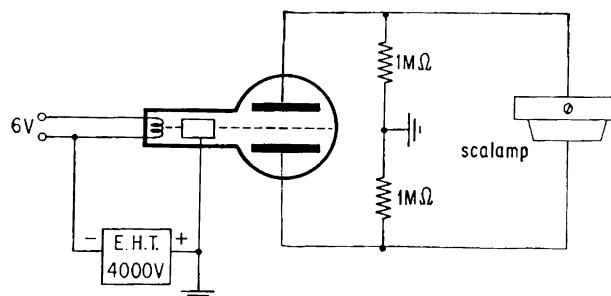


Fig. 222

Now bring a magnet close to the side of the tube so that the electron beam is deflected upwards and touches the upper plate. Is there now a voltage between the plates? Which plate is negative?

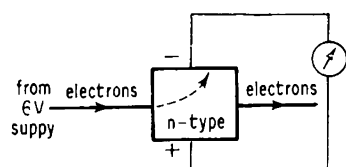


Fig. 223

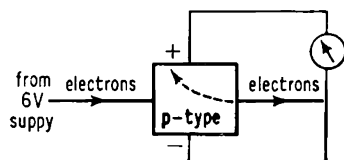


Fig. 224

If a beam of positively charged particles had been flowing in the *opposite* direction through the tube, would the same magnetic field have caused them to bend upwards or downwards? Would the top plate have been negative or positive with respect to the other?

If a piece of n-type germanium is connected to a d.c. supply, no voltage should appear between the upper and lower sides. If, however, a magnet is brought close to the germanium so that the charge carriers are deflected upwards as shown in Fig. 223 and if the charge carriers are negative, we might expect the upper side to become negative with respect to the lower side. This voltage is called the *Hall voltage* and can be read on a voltmeter. If the charge carriers are positive, the Hall voltage should be reversed. You can study these voltages in the following demonstration.

Demonstration 7.5. Connect a piece of n-type and a piece of p-type germanium₁₀ in series with a 6 volt d.c. supply. Connect the sides of the n-type germanium to a sensitive microvoltmeter and note the deflection when a ticonal magnet₁₀ is brought close to it (Fig. 225). Repeat the experiment with the meter connected to

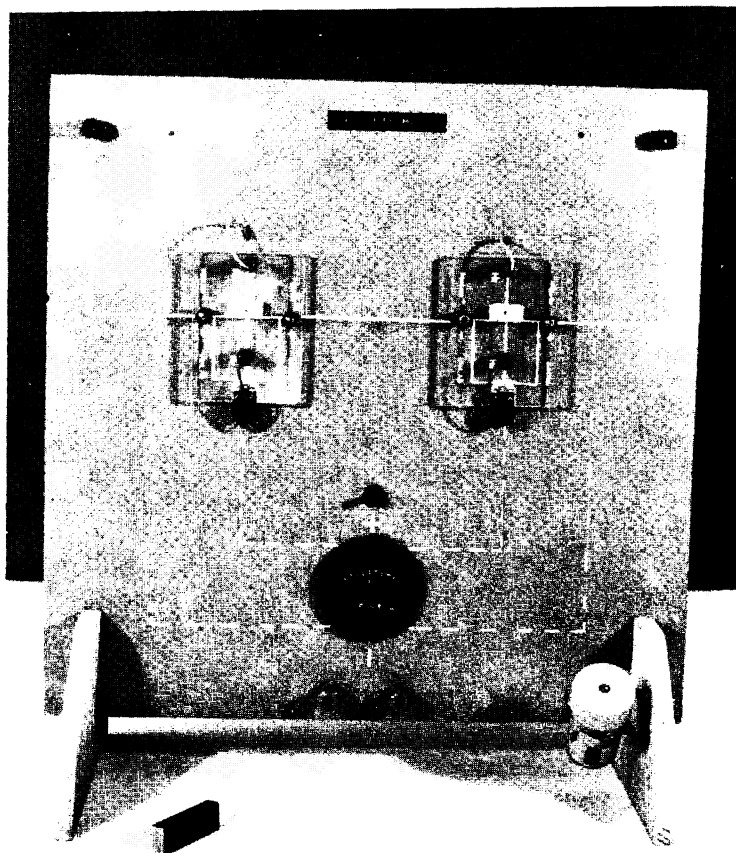


Fig. 225

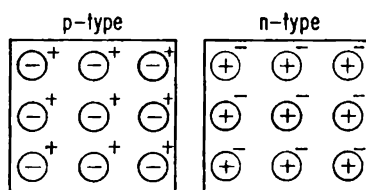


Fig. 226

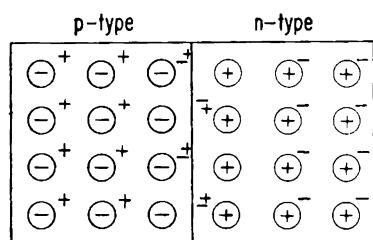


Fig. 227

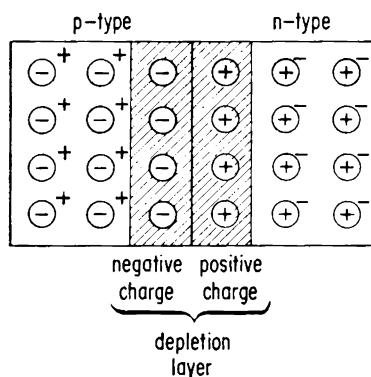


Fig. 228

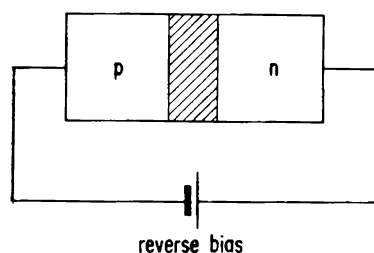


Fig. 229

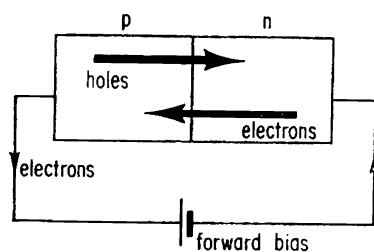


Fig. 230

the piece of p-type germanium. Explain your results in terms of charge carriers.

(The Hall voltage produced across a semiconductor in a magnetic field may be used as an indication of the *strength* of the field.)

p-n Junction

Pieces of n- and p-type germanium are shown in Fig. 226. The circled charges are static and the other + and - signs represent the mobile charge carriers.

A single crystal containing both p- and n-type germanium can be grown. It is called a p-n junction. Although both materials are electrically neutral, a few electrons migrate through the junction and enter the p-type germanium and a few holes migrate into the n-type germanium (Fig. 227).

The carriers which have 'changed ends' recombine with their opposite numbers, thus leaving a narrow region of static negatively charged atoms on the p-type side of the junction and a region of positively charged atoms on the other (Fig. 228). A *potential barrier* is therefore built up between the two types of material and this prevents any further flow of charge across the junction. The shaded region in Fig. 228 is called the *depletion layer*. It contains no charge carriers and is therefore a good insulator.

If now a battery is connected as shown in Fig. 229, the barrier potential is increased and no charge can flow across it. The battery is said to be connected in the *reverse* direction.

If a battery with an e.m.f. greater than the barrier potential is connected as shown in Fig. 230, the depletion layer disappears, the electrons and holes recombine and charges flow round the circuit. The battery is said to be connected in the *forward* direction.

The symbol for a p-n junction or similar solid-state device is shown in Fig. 231. The triangle points in the direction of hole current.

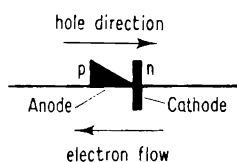


Fig. 231

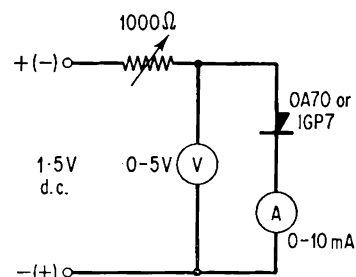


Fig. 232

Experiment 7.6. Use the circuit illustrated in Fig. 232 to investigate the variation of current through a diode (e.g. 1GP7₁₄ or OA70). Plot a graph showing how the current varies with the voltage applied in each direction. How does the graph compare with that for the current through a carbon resistor? Which is linear? Which is non-linear?

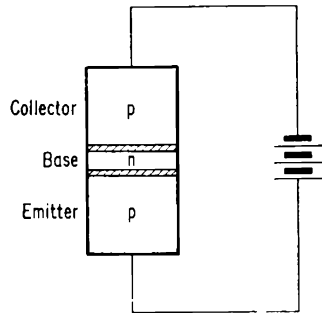


Fig. 233

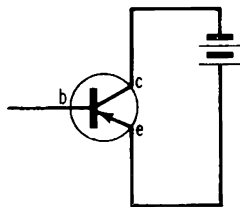


Fig. 234

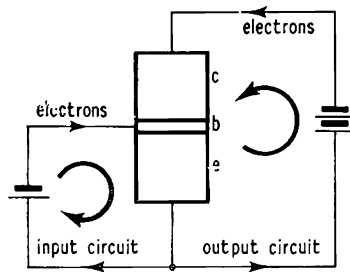


Fig. 235

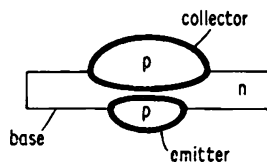


Fig. 236

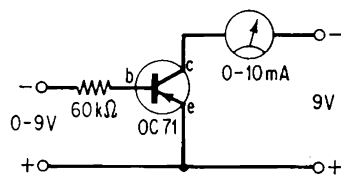


Fig. 237

Transistors

In 1948 three American scientists discovered that by using a sandwich of p- and n-type semiconductors it was possible to amplify small electric currents. Eight years later these scientists, William Shockley, John Bardeen and Walter Brattain, shared the Nobel Prize in physics for their invention. The tiny sandwich, which they called a *transistor*, has in a few years revolutionised the entire electronics industry. It will do most of the jobs which the thermionic valve previously did—amplify, oscillate, switch—yet it is smaller, lighter, cheaper and much more efficient than any valve. The elaborate electronic equipment now used in satellites and computers contains thousands of transistors and junction diodes.

One type of transistor (Fig. 233) consists of a very thin piece of n-type germanium (base) sandwiched between two pieces of p-type germanium (emitter and collector). In a p-n-p transistor the terms emitter and collector are used with reference to the *holes*; that is, holes leave the emitter and arrive at the collector. The arrow in the symbol for a transistor (Fig. 234) indicates the direction of hole movement.

In a transistor a depletion layer is formed at each junction, so that when a battery is connected between the emitter and the collector as shown in Fig. 234 there will be practically no current in the external circuit.

If, however, the emitter-base junction is forward biased, by connecting a battery as shown in Fig. 235, the depletion layer between these regions disappears and holes move freely from the emitter to the base. Some of these holes recombine with electrons from the input circuit but, as the base is extremely thin (less than 10^{-5} m), the majority pass right through into the collector, which is negative with respect to the base. There they recombine with electrons from the external circuit (output).

If the input current stops, the emitter-base depletion layer is again formed, thus blocking further hole movement and stopping the output current.

In practice it is found that a small current flowing in the input circuit can produce a very much larger current in the output circuit; that is, a small current in the input circuit *controls* a large current in the output circuit, and small *changes* in the input current cause proportionally greater current *changes* in the output circuit. The device therefore operates as a current amplifier.

Experiment 7.7. Use a powerful magnifying glass to examine a transistor (Fig. 236). Either remove the cap from an old transistor or use an OCP71 which has a transparent case.

Problem 1. Why do transistor radio sets come on immediately while older mains-operated receivers take time to 'warm up'?

Transfer Characteristic

Experiment 7.8. Use the circuit illustrated in Fig. 237 to find how the current in the collector circuit of a transistor (I_c) varies with the changes in base current (I_b). A 9 volt grid bias battery provides a suitable tapped source for the input circuit. If we

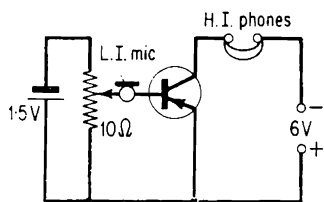


Fig. 238

ignore the resistance between the base and the emitter, we can find the base current as follows.

$$\text{Base current} = \frac{\text{battery voltage}}{60,000}$$

Plot a graph showing how the collector current varies with base current for a fixed collector voltage. The graph is called the *transfer characteristic* of the transistor.

The slope of this line $\frac{\Delta I_c}{\Delta I_b}$ is the current amplification factor. Calculate this from your graph.

Transistor Amplifier

Experiment 7.9. Build a simple transistor amplifier, using a low impedance magnetic earpiece as a microphone and a high impedance earphone in the collector circuit (Fig. 238).

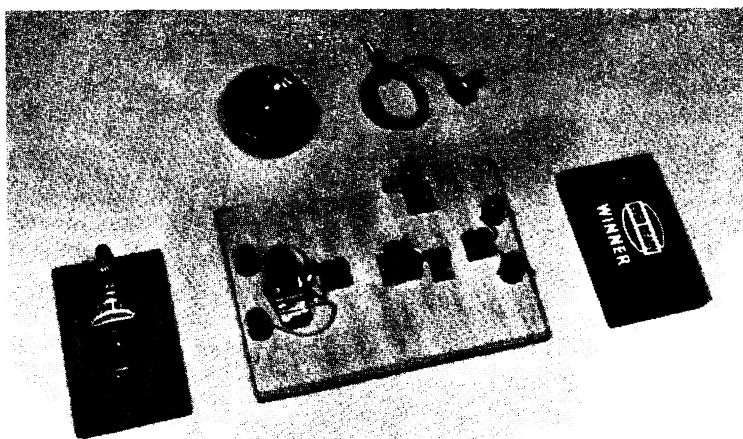


Fig. 239

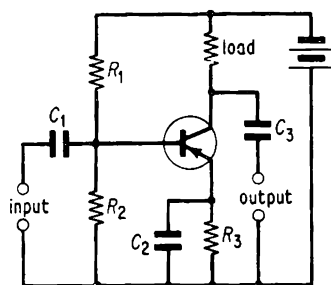


Fig. 240

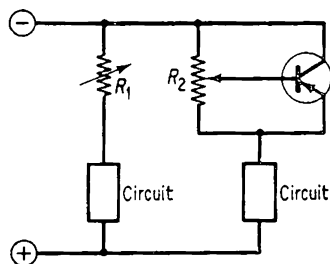


Fig. 241

(A practical layout (unwired) is shown in Fig. 239. Only a screwdriver, wire stripper and some wire are needed to complete the circuit.)

Optional Extras

Problem 2. The above diagram shows a practical transistor circuit. Can you suggest why R_1 , R_2 are fitted? R_3 and C_2 prevent large currents flowing through the transistor owing to temperature variations. Can you explain how these components prevent large current surges?

What purpose do C_1 and C_3 serve?

Practical Puzzle 3. Fig. 241 shows two ways of changing the value of a large current through a circuit. R_1 is a large expensive rheostat. R_2 is a small cheap variable resistor connected to a power transistor. Such a transistor can allow large currents to pass provided it is screwed to a heat sink (usually a metal chassis). A power

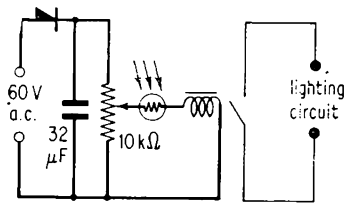


Fig. 242

transistor and small variable resistor are smaller and cheaper than a large rheostat. Can you explain how they do the same jobs?

Can you devise a circuit in which a power transistor (e.g. OC35) is used in place of a relay? Explain why a relay is normally used and how the power transistor does the same job.

Project 7.10. The circuit illustrated in Fig. 242 will automatically switch on an electric light at dusk. A rectifier capable of delivering about 20 mA can be used in conjunction with an ORP12 photoconductive cell and a 10 kilohm relay (5 mA). When the daylight shining on the cell falls below a certain value, the relay contacts close and complete the lighting circuit.

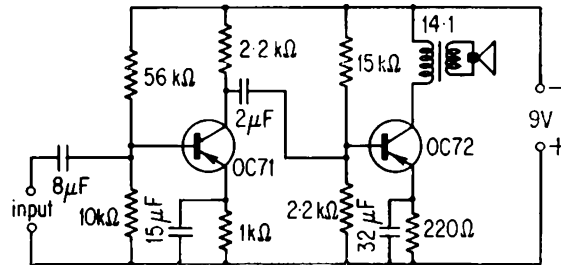


Fig. 243

Project 7.11. Fig. 243 shows the circuit of a small transistor amplifier which you may like to build. It may be used as a gramophone amplifier.

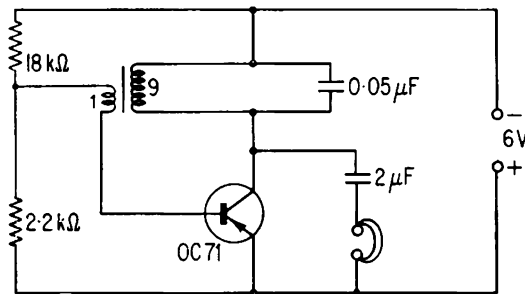


Fig. 244

Project 7.12. A simple transistor oscillator is illustrated in Fig. 244. It can be built from a 9 : 1 transistor output transformer and an OC71. How could you vary the frequency of oscillation?

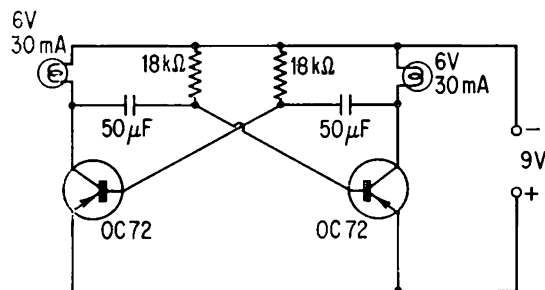


Fig. 245

Project 7.13. A fascinating multivibrator can be made from two OC72 transistors using the circuit shown in Fig. 245. The bulbs will flash off and on alternately.

Project 7.14. Try to find out a little about the construction and use of zener diodes, tunnel diodes, field effect transistors (F.E.Ts) and metal oxide semiconductor transistors (M.O.S.Ts).

Visual Aids

Charts: The Transistor Story₃₀ C797.

16 mm Films: The World of Semiconductors₃₁ 4DCF.2655.
Transistors₃₅.

The Principles of the Transistor₃₄.

Swinging Electrons

CHAPTER 8

Why and How is A.C. Produced?

You may wonder why we bother to produce alternating current at all when direct current is perfectly able to give us heat and light, to operate our radio and television sets, and to turn electric motors. In one sense this is rather like asking why we bother with the messy business of getting milk from cows when we can get it so easily from the milkman.

Apart from the small amount of electricity we obtain from cells and batteries, practically all the electricity used in the world today is produced as a.c. It is, at present, much easier to produce a.c. than d.c., and it would be very difficult and expensive—and indeed pointless—to change the a.c. into d.c. for most purposes. Even if electricity were generated as d.c., and there are indications that this may soon be practicable, it would normally have to be changed to a.c. to be transmitted over long distances. D.C. power transmission is sometimes used and has the advantage that the cables can then be run underground more economically. It is, for example, used to carry power under the English Channel. The overall cost of d.c. transmission is, however, still high, and overhead cables carrying alternating current are likely to be with us for some time to come.

In the following experiments you can discover ways of producing alternating current by electromagnetic induction. This may be done by causing a conductor to vibrate near a magnet or making a magnet vibrate near a conductor. A more practical alternative is to rotate a magnet near a conductor or make a conductor rotate near a magnet.

Experiment 8.1—Vibrating Conductor. Use the magnets from the electromagnetic kit_{N92} as shown in Fig. 246 to produce an alternating current when the coil is moved up and down between the poles. A 2–0–10 mA meter is suitable.

Experiment 8.2—Vibrating Magnet

(i) Suspend two small ticonal magnets_{N92} fixed end to end and a 200 g mass on a spring_{N2A} so that the magnet dips into a 250-turn coil₁₀ (LB-3). Use them to produce a slow alternating current, which may be indicated on the 2–0–10 mA meter. Alternatively, use the 5000-turn winding and a C.R.O. (Fig. 247). Another arrangement is illustrated in Book 2, page 157.

(ii) Magnetise a tuning fork and place it close to a 5000-turn coil₁₀ (LB-3) on a C-core (Fig. 248). Use an oscilloscope to display the output from the coil.

Experiment 8.3—Rotating Magnet. Use the electromagnetic kit to construct a simple alternator in which two magnadur magnets rotate close to a 250-turn coil₁₀ (LB-3) on a C-core. The magnets

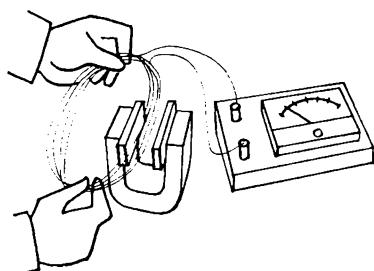


Fig. 246

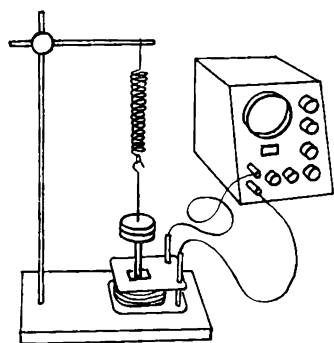


Fig. 247

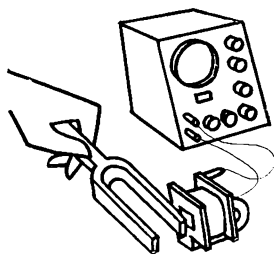


Fig. 248

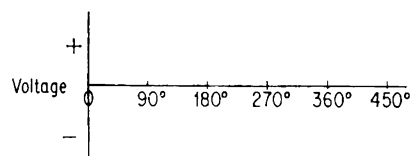


Fig. 251

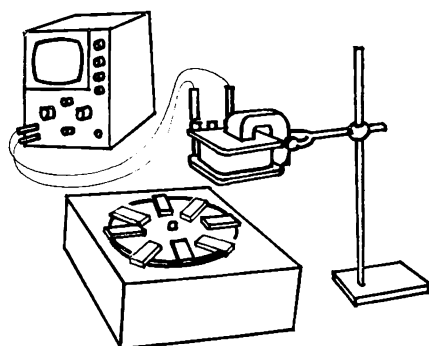


Fig. 252

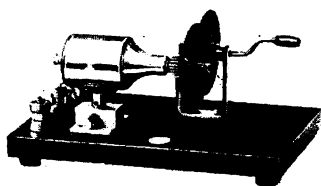


Fig. 253

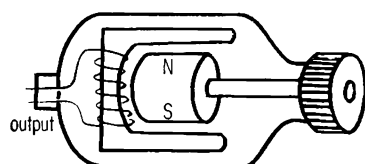


Fig. 254

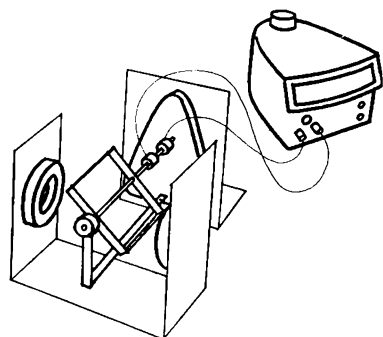


Fig. 255

may be fixed on either side of a knitting needle using a small piece of plasticine between them. The output can be seen on a C.R.O. (Fig. 249) or read on a 2-0-10 mA meter.

An alternative arrangement is shown in Book 2, page 158.

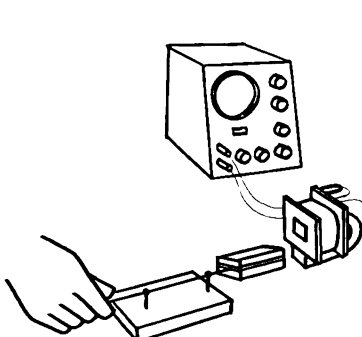


Fig. 249

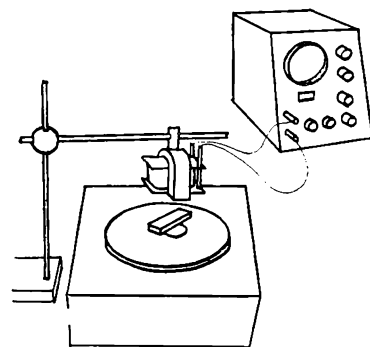


Fig. 250

Demonstration 8.4—Rotating Magnets

(a) Attach a strong horse-shoe magnet or ticonal bar magnet₁₀ to the centre of a gramophone turntable by means of a piece of plasticine. Place a 5000-turn coil above the magnet as shown in Fig. 250, and feed the output to a 0.5 mA centre zero meter or oscilloscope with a long persistence tube₁₂ (S51E).

Complete the graph (Fig. 251) showing how the output varies with the angle of rotation of the turntable. Assume that the output is zero at 0°.

(b) Alternatively place 8 magnadur magnets with their uppermost poles alternately north and south on a gramophone turntable as shown in Fig. 252. Use the 5000-turn coil and feed the output to an oscilloscope.

Demonstration 8.5. In a bicycle dynamo_{N103} (Fig. 253) a magnet rotates close to a coil (Fig. 254) to produce an alternating current. Feed the output of such a dynamo to an oscilloscope, and note the change of frequency and amplitude as the speed of rotation is increased.

Demonstration 8.6—Rotating Conductor. Most alternators consist of a coil rotating in a magnetic field. Fig. 255 illustrates a model of such a coil, placed between two magnetic pucks_{N169}. Connect the output from the slip rings to a centre-zero meter and note the position of the coil when the current is maximum and when it is zero.

Measuring A.C.

1. Frequency

The number of complete to and fro swings of current every second is called the *frequency*. The unit of frequency is the Hertz (Hz), named after the German physicist Heinrich Rudolf Hertz. 1 Hz is 1 cycle per second (c/s).

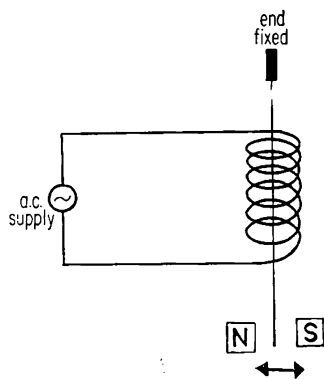


Fig. 256

Problem 1. An iron strip is free to vibrate inside a coil through which a.c. flows (Fig. 256). If one end of the strip passes between the poles of a horse-shoe magnet, can you explain why the strip vibrates? How could you use a ticker-timer to find the supply frequency?

Experiment 8.7. Use a calibrated signal generator and an uncalibrated oscilloscope to find an unknown frequency, such as the ripple frequency from the d.c. output of the low voltage power pack_{N104}.

2. Voltage

Before considering how to measure alternating voltage, we ought to ask exactly what it is we *want* to measure. If you buy a bulb marked '6 volts' you would expect it to light up equally brightly on a 6 V dry battery producing d.c., or a 6 V bicycle dynamo producing a.c. As the 'volt' is defined as one joule per coulomb, you would expect each 6 volt source to produce the same number of joules of heat or light for every coulomb of charge flowing through the bulb. The voltage which is capable of producing the same heating effect as the 6 V battery (d.c.) is called the *effective* or *r.m.s.* value of the alternating voltage.

$$6 \text{ volts (d.c.)} \equiv 6 \text{ volts r.m.s. (a.c.)}$$

R.M.S. stands for 'root mean square'. You can discover why it is so named later if you go on to study higher maths! For the moment you can think of it simply as the value of an alternating voltage which will cause heat to be produced in a given resistor at the same rate as will a direct voltage of that value. In the next experiment you can see how the peak value of an alternating voltage is related to the r.m.s. value.

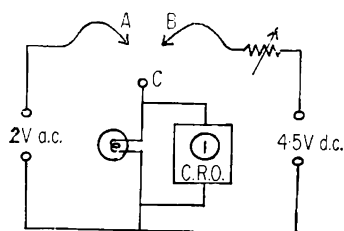


Fig. 257

Experiment 8.8. Use the low voltage power unit _{N104} to supply 2 volts a.c. and the low frequency a.c. generator_{N170} as a variable resistance (one yellow and one black terminal) in the circuit shown in Fig. 257. Connect the Serviscope minor₁₂ across a 2.5 V 0.3 A bulb, and join A to C using a crocodile clip. With the time base switched off, adjust the gain control to produce a vertical line 10 units in length.

Now remove clip A and join B to C. Adjust the variable resistance (generator wheel) until the bulb glows as brightly as before. A photographic exposure meter can help you here. Check that the bulb is equally bright by switching A to C and then B to C several times. Note the deflection of the spot in units on the C.R.O. screen when B is joined to C.

Remembering that the 10 units represent two 5 unit swings of alternating voltage (Fig. 258), can you state the direct voltage equivalent to 5 volts (peak) a.c.? What is the direct voltage equivalent to 1 volt (peak) a.c.?

Complete the following statement.

1 volt (peak) a.c. is equivalent to . . . volts d.c.

Finally, measure the two equivalent voltages using appropriate a.c. and d.c. meters.

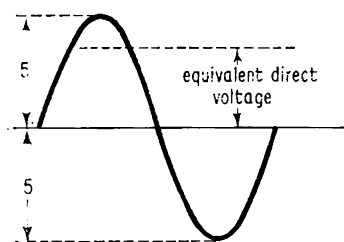


Fig. 258

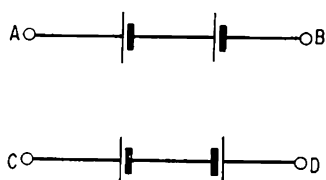


Fig. 259

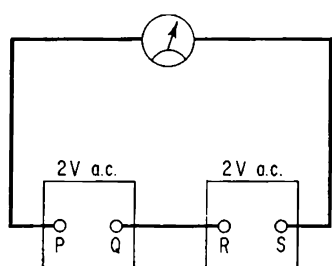


Fig. 260

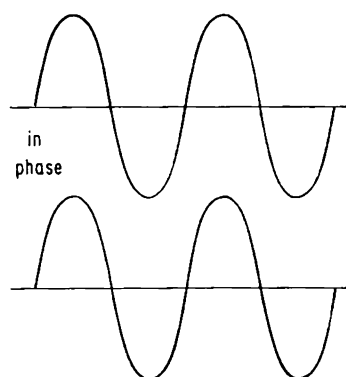


Fig. 261

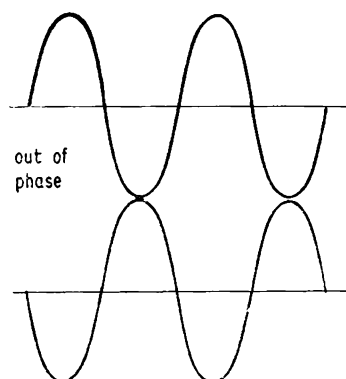


Fig. 262

A.C. voltmeters are normally calibrated in effective (or r.m.s.) values, and unless it is stated otherwise we will in future assume that when we speak of alternating voltage it is this value that is intended.

Adding Alternating Voltages

Problem 2. If each cell in Fig. 259 has an e.m.f. of 1.5 volts, what is the voltage across AB? What is the voltage across CD?

Experiment 8.9. Connect two low voltage power supplies in series (Fig. 260), and measure the voltage across PS with an a.c. voltmeter or a C.R.O.

Now reverse the connections to R and S, and again measure the total voltage.

When two alternating voltages are 'in phase' (Fig. 261), the total voltage is the sum of the two separate voltages. When they are 'out of phase' (Fig. 262) the total voltage is their difference. Provided the frequency of each voltage is the same, we can add, or subtract, alternating voltages in this way.

3. Current

(a) Moving coil meter and rectifier

A normal moving coil meter is not, by itself, suitable for measuring a.c. *Why not?* (3) Of course such a meter can be used if the a.c. is rectified first (Fig. 263).

To allow current to flow through the meter during both half-cycles a *full wave rectifier* or *bridge rectifier* is normally used. This is illustrated in Fig. 264. Can you work out the operation of such a circuit? Most multirange meters (e.g. AVO) use this type of circuit for their a.c. ranges.

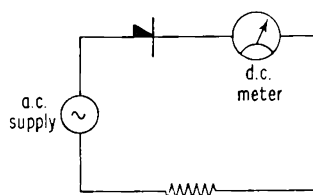


Fig. 263

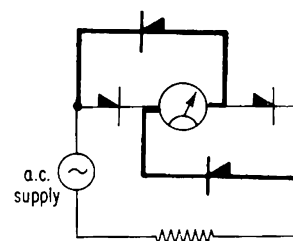


Fig. 264

(b) Moving iron meter

Perhaps the cheapest form of a.c. meter is the moving iron meter. The a.c. flows through a coil which then attracts a lump of iron attached to a pointer. As the attraction is independent of the direction of the current, this meter indicates a.c. Fig. 265 illustrates a simplified form of moving iron meter.

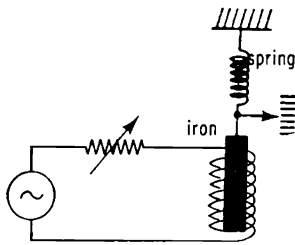


Fig. 265

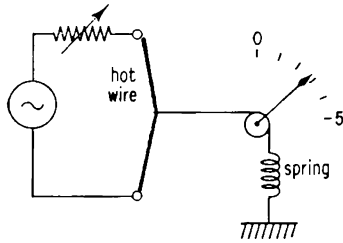


Fig. 266

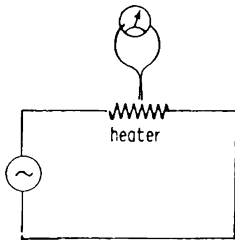


Fig. 267

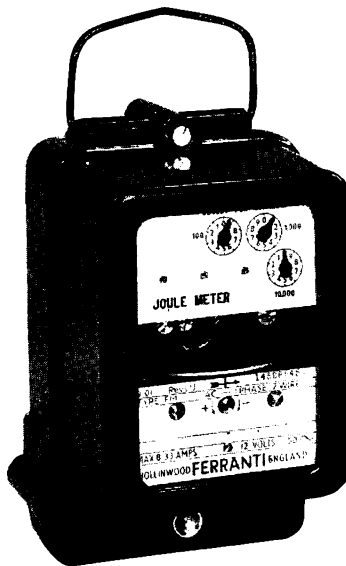


Fig. 268

(c) Meters depending on heating effect

The heating effect of a current does not depend on the direction, so that this effect can be used to indicate the strength of an alternating current.

(i) In the hot-wire meter a wire *expands* when heated by the current (Fig. 266).

(ii) In the thermo-junction ammeter the current heats a thermocouple and the output is read in a moving coil meter (Fig. 267).

4. Power and Energy

The rate at which electrical energy is transformed is measured in *joules per second* or *watts*.

$$\text{volts} = \text{joules per coulomb}$$

$$\therefore \text{joules} = \text{volts} \times \text{coulombs}$$

$$\therefore \text{joules per second} = \text{volts} \times \frac{\text{coulombs}}{\text{seconds}}$$

$$\therefore \text{watts} = \text{volts} \times \text{amperes}$$

To measure power it is therefore necessary to measure the voltage and the current and to multiply them together. This method is perfectly satisfactory when dealing with direct current as the voltage and current are always in step or *in phase*. It is not, however, possible to use this method when dealing with alternating currents if the current and voltage are not in phase.

Fortunately there is an instrument which enables us to find (in joules) the total amount of energy transformed, so that we can find the power by noting the energy transformed in a certain time. The instrument is called a joulemeter (Fig. 268), and we will use it later to find the amount of energy being transformed by various components. The speed at which the aluminium disc in the meter rotates will give us a qualitative idea of power.

The theory behind the joulemeter and its domestic counterpart, the kilowatt-hour meter, is too difficult to discuss here, but this need not prevent our using it. After all, very few drivers know how an internal combustion engine works!

Most electrical household equipment is essentially resistive, so that we can calculate power, for most practical purposes, as 'volts times amps' using r.m.s. values of voltage and current. The following quantities are still applicable

Flow rate: Current (I) in amperes $1\text{A} = 1 \text{ coulomb per second}$

Pressure difference: p.d. (V) in volts $1\text{V} = 1 \text{ joule per coulomb}$

Opposition: resistance (R) in ohms $1\Omega = 1 \text{ volt per ampere}$

Work: energy (E) in joules $1\text{J} = 1 \text{ volt coulomb}$
 $= 1 \text{ watt second}$

Rate of Working: power (P) in watts $1\text{W} = 1 \text{ joule per second}$
 $= 1 \text{ volt ampere}$

Transformers

We have already seen that a changing current in one circuit can induce an e.m.f. and hence a current in another circuit close to it. As an alternating current is changing all the time it should be possible for it to continue to induce an e.m.f. in a nearby circuit.

An alternating current in a coil, wound round a laminated iron core, will produce an alternating magnetic field. In the following experiment you can see what happens when a second coil is slipped over the core so that the magnetic field through the coil is changing continuously.

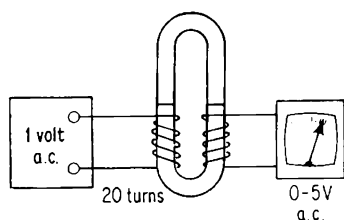


Fig. 269

V_p	V_s	?	T_p	T_s	?

Fig. 270

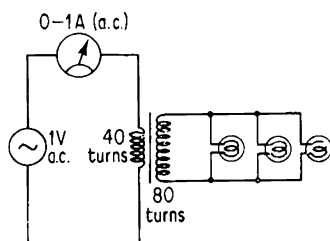


Fig. 271

Experiment 8.10—Voltage Ratio. Apply 1 volt a.c. from the low voltage supply to a 20-turn coil (primary) wound on a C-core (Fig. 269). Can you find a way of obtaining 2 volts and then 3 volts a.c. across a second coil? Does it matter whether a second C-core is placed on top of the first? Why is this? Can you replace the second C-core with a solid iron bar without affecting the secondary output? Why is this?

Does it matter whether the second coil (secondary) is loosely wound or tightly wound round the arm of the C-cores when two of them are slipped together? Does it matter where on the complete laminated core the secondary is wound?

With a 2:1 ratio transformer what is the frequency ratio? Check your answer with a C.R.O.

Complete the following table, and see if you can discover any connection between the primary and secondary voltages (V_p and V_s) and the number of turns in the primary and secondary circuits (T_p and T_s).

Experiment 8.11—Current. Wind a 40-turn coil on a C-core and connect it via an ammeter to the 1 volt a.c. supply (Fig. 271). Wind an 80-turn coil on another C-core and clamp the two cores together. With the 80-turn secondary on open-circuit, adjust the cores to give minimum primary current. Note this current and then connect one, two and finally three bulbs (2.5 V 0.3 A) across the secondary, noting the primary current each time.

How is the primary current affected by the current in the secondary? Why is there a current in the primary when no current flows in the secondary? This primary current is called the *magnetising current*.

(A 0–10 mA a.c. meter may be used with a few centimetres of fine Eureka wire across its terminals to act as a shunt. Unilab LB-2 coils are suitable, with 60 turns in the primary and 120 in the secondary. Alternatively one LB-2 coil may be used as an auto-transformer.)

Demonstration 8.12

(i) **Voltage Ratio.** Use a Berco 'wind-a-volt' toroidal transformer₁₅ to compare various voltage ratios and turns ratios when there is no load on the secondary (Fig. 272).

(ii) **Current Ratio.** Insert a 0–1 A a.c. meter in the 600-turn primary circuit of the Berco transformer, and connect a 0–10 A a.c. meter across a 6-turn secondary wound from heavy wire.

Compare the current ratio and turns ratio when the secondary is effectively short circuited by the ammeter. Repeat this experiment with various inputs to the primary circuit.

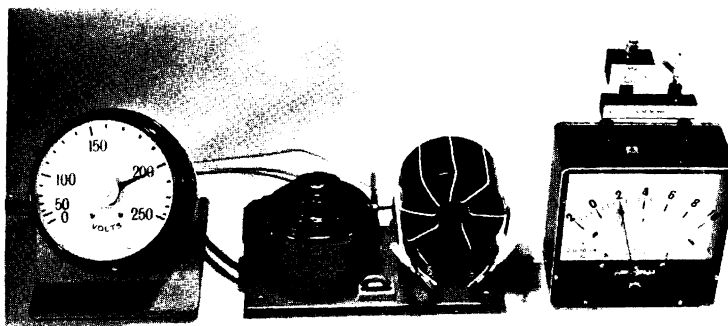


Fig. 272

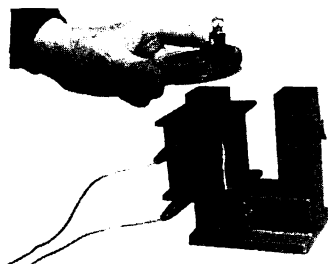


Fig. 273

Demonstration 8.13. Fit a 1200-turn coil to the yoke of the demountable transformer_{N147}. Apply 240V a.c. to the coil, and then bring close to the yoke a 50-turn coil which is connected to a 2.5V 0.2A bulb (Fig. 273). What causes the bulb to light? What 'links' the two coils? What happens when the linkage is increased? How can the maximum linkage be achieved?

Will the bulb still light if the 50-turn coil is immersed in a jar of water? What does this tell you?

Efficiency of a Transformer

A transformer is a machine. Energy is fed into the primary circuit and taken from the secondary circuit. In the following experiment you should compare the input of energy, measured by a standard kilowatt-hour meter, with the output of energy, measured by a 12 volt joulemeter.

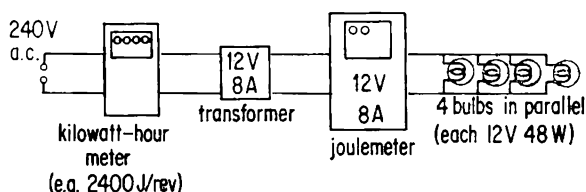


Fig. 274

Demonstration 8.14. A mains transformer with 12V 8A output₁₆ is suitable for this experiment. Use the circuit shown in Fig. 274 to find the input and output of energy and hence to calculate the efficiency of the transformer. Why is the efficiency not 100 per cent?

Demonstration 8.15

(i) Use a demountable transformer kit_{N147} to investigate the current taken by the primary circuit and the voltage across the secondary on open circuit (Fig. 275) when

- (a) there is no yoke across the laminated U-core,
- (b) a laminated iron yoke is fitted to the U-core,
- (c) a solid iron core and yoke are used.

Which makes the most efficient transformer? What is the efficiency of the transformer when the secondary is on open circuit?

(ii) Now repeat the experiment with a 3.5V 0.3A bulb connected across the secondary. Is this an efficient transformer? Why is a real transformer so much more efficient?

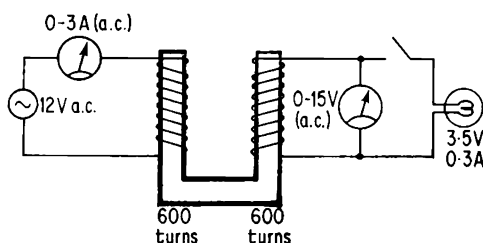


Fig. 275

Losses

Although the efficiency of some fully loaded transformers is very high, no transformer is 100 per cent efficient. Some of the input energy is always 'lost' as far as the secondary is concerned.

1. Current flowing through the copper coils causes the windings to heat up. Energy lost in this way is called *copper loss* or I^2R loss. It can be reduced by winding the transformer with heavy copper wire.

2. The iron core is in a changing magnetic field and so has induced currents flowing in it. These *eddy currents* produce heat in the core. Eddy currents may be reduced by using a laminated core.

3. In one cycle the core has to be magnetised, demagnetised, magnetised again in the opposite direction and again demagnetised. Energy is required to do this, i.e. to rotate the domains. This is called *hysteresis loss* and can be reduced by using special alloys for the core.

All of these losses reduce the overall efficiency of a transformer. As a transformer is less than 100 per cent efficient, the following ratios are only *approximately* correct for transformers in normal use.

$$\frac{V_p}{V_s} \approx \frac{t_p}{t_s}$$

$$\frac{I_p}{I_s} \approx \frac{t_s}{t_p}$$

Explain what these symbols represent and state when these relationships are most nearly valid in practice. (4)

Use of Transformers

One of the most important uses of a transformer is to provide any required alternating voltage efficiently. Suppose for example that a bulb rated at 12V 2A has to be supplied from 240V mains. A resistor could be used in series (Fig. 276).

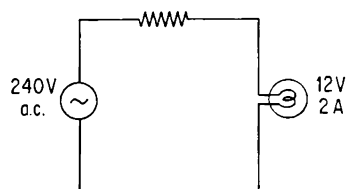


Fig. 276

What must be the total resistance in the circuit to produce a current of 2 amperes? (5) What is the resistance of the bulb? (6) What must be the value of the resistor? (7) What is the input of energy to the circuit each second, i.e. power? (8) What is the energy supplied to the bulb every second (power) and what happens to the remainder of the energy? (9) What is the efficiency of this system? (10)

Even a poor transformer has a vastly greater efficiency than this. Approximately what turns ratio of transformer would be needed to supply this bulb from the mains? (11)

Problem 12. To obtain low voltages from 240V a.c. mains for electric bells, electric blankets, electronic equipment, accumulator chargers, etc., transformers are used. What turns ratios would be needed to supply from 240V a.c. (i) 12V, (ii) 2V, (iii) 8V, (iv) 600V?

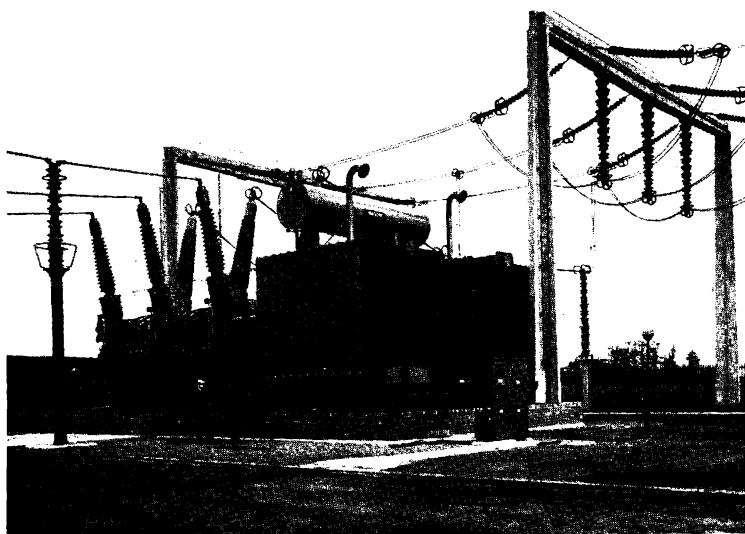


Fig. 277

The National Grid

To transmit electrical energy over long distances transformers are used first to step up the voltage from the generators to 400 kV (Super Grid) and then to step it down again at the other end of the transmission lines. In the following demonstration you can see why this is necessary.

Demonstration 8.16. A bicycle dynamo can be used to represent the generating station. In Fig. 278 the dynamo is driven by an electric motor supplied from a variable transformer.

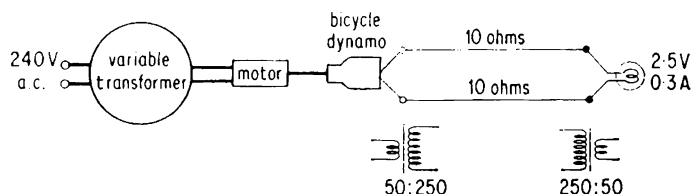


Fig. 278

Connect a 2.5V 0.3A bulb across the dynamo terminals and adjust the speed of the motor until the bulb glows brightly. Now connect the bulb to the dynamo through two long wires each having about 10 ohms resistance. These represent the wires carrying the electrical energy from the power station to the consumer. Does the bulb light up now when the dynamo is running at the same speed as before?

Finally use two transformers, each made from a double C-core with a 50-turn winding and a 250-turn winding, one to step up the output from the dynamo and the other to step down the voltage at the other end of the line. What difference do you observe?

(Unilab LB-2 and LB-3 coils or two bell transformers are suitable.)

To transmit energy at a certain rate (power = VI) along the lines, we can have a large voltage and a small current or a small voltage and a large current. *Will the power loss in the lines depend on the current in them, the voltage between the ends of each line, or the voltage between the two lines?* (13) *By inserting the two transformers in the circuit above will the current in the lines be increased or reduced?* (14) *Will the loss of power due to the heating in the lines be greater with or without the transformers?* (15)

Problem 16. *If the total resistance of a power line is 2 ohms what power is lost when it carries 1 ampere? 100 amperes?*

Problem 17. *A 200 volt alternator can deliver 2000 watts. What will the current be? If it feeds into power lines having a total resistance of 10 ohms, what will be the power lost?*

If now a transformer is used to step up the voltage to 2000 volts, what current will now flow in the lines when 2000 watts is being delivered? What power will now be lost in the lines?

Demonstration 8.17. Large currents can be produced in a single turn secondary of a transformer. This can be used to melt solder in a copper ring (Fig. 279). Enough heat to melt an iron nail can be produced from a secondary of a few turns.

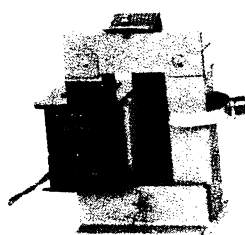


Fig. 279

Problems

18. *A transformer to operate on 240V has 1000 turns in its primary. It is to be used to supply a 12V model railway which takes 1 ampere. If the transformer is assumed to be 100 per cent efficient, how many turns would be needed in the secondary winding? What would be the primary current?*

19. *How would you supply a 6V bell from 240V mains? Would you put the press button in the 6V or 240V circuit? Why?*

20. *An audio amplifier to be operated from a 240V supply has a mains transformer with 1440 turns in the primary winding. If the*

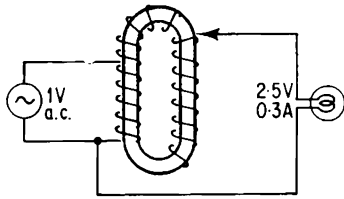


Fig. 280

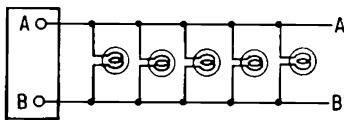


Fig. 281

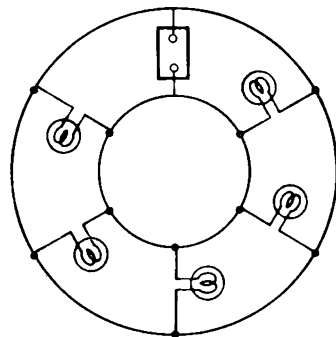


Fig. 282

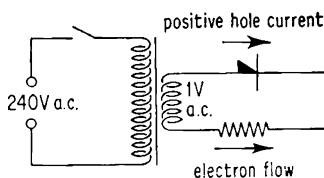


Fig. 283

secondaries are marked 300–0–300V, 6V and 5V how many turns would you expect in each? What assumption have you made in your calculations?

21. In order to heat a shed a farmer ran a long length of power cable of negligible resistance from his house to the shed. If the maximum safe current for the cable was 20 amperes and a 125 volt a.c. supply was used, what would be the maximum permissible power rating for the heater? One very cold winter he wanted to use two of these heaters. How could he do this, using the original cable? Draw the circuit and describe any additional components you insert.

22. The total resistance per kilometre of two power transmission lines is 2 ohms. If the lines carry 40 amperes at 275,000 volts, find the power loss per kilometre. What is the voltage available 100 kilometres from the power station when a current of 40 amperes is flowing?

If the same transmission lines were used with a 250 volt supply and the required voltage at the other end of the 100 kilometre lines was 200 volts, what would be the maximum permissible current?

Project 8.18. Use two C-cores and some wire to wind a variable auto-transformer. Strip a piece of insulation off each turn to enable you to slide one of the output connections round the coil and so vary the output. Feed in 1 volt a.c. from the low voltage power supply and try to light a 2.5V 0.3A bulb.

Project 8.19. Build a model of a 13 ampere domestic 'ring circuit' using the 2V a.c. output from the low voltage power pack and a number of 2.5V 0.3A bulbs. Compare the results when the same number of bulbs are connected as shown in Figs. 281 and 282. The latter arrangement may be achieved by connecting A to A' and B to B'. What are the advantages of the ring circuit?

(Two 60 cm lengths of 26 gauge Eureka wire of 2.85 ohms per yard and 5 bulbs are suitable.)

Would you expect each of the plugs used in a 13 ampere ring circuit to be fused with a 13 ampere fuse? Explain your answer carefully.

Rectification

You have seen that the thermionic diode (page 80) and the p-n junction (page 98) allow charge to flow in one direction only. These and other rectifiers may be used to change alternating current into unidirectional current (pulsating d.c.).

Experiment 8.20

(i) Connect a half wave rectifier (Rec 50A₁₄) and a 600 ohm resistor to the 1 volt a.c. output of the low voltage power unit (Fig. 283). Study the voltage waveform across the resistor using a C.R.O. Can you explain the pattern?

(ii) Examine any change in the waveform when various capacitors (0.1 μ F–500 μ F) are wired across the resistor.

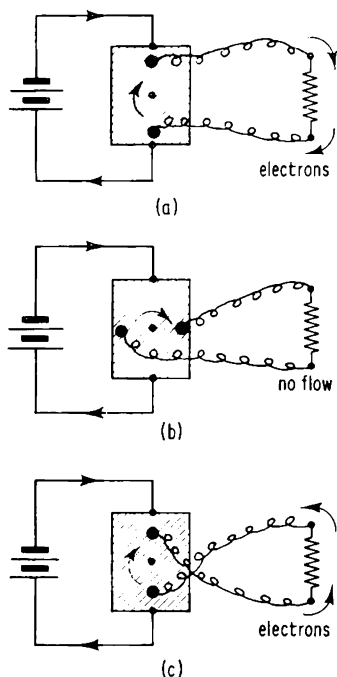


Fig. 284

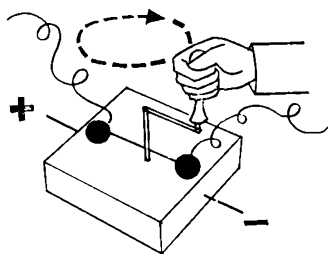


Fig. 285

Artificial A.C.

Although in practice alternating current is generated by rotating magnets or coils, a simple device can be used to produce slow or low frequency a.c. from a dry battery.

To understand the principle of this slow a.c. generator_{N170}, imagine a dry battery connected to the ends of a carbon block (Fig. 284 (a)). Two contacts (shown black and red) rest on the block. They are fixed to an insulator mounted on a spindle which can be rotated as shown in Fig. 285. When the contacts are in the position of Fig. 284 (a) the black contact will be negative with respect to the red one and electrons will flow down through a resistor wired to the contacts.

When the contacts are in position (b) there will be no p.d. between them and no current will flow through the resistor. When rotated to position (c) the black contact will be positive with respect to the other and the electrons will flow up through the resistor. Continuous rotation of the spindle will cause the current through the resistor to change direction repeatedly. In other words, alternating current will be produced. In practice the carbon block is replaced by a flat coil of resistance wire, and the connections from the contacts are fed via slip-rings to the resistor.

Experiment 8.21

(i) Connect a 6V battery to a slow a.c. generator_{N170} and measure the a.c. output with an a.c. voltmeter. Gradually increase the speed of rotation of the contacts, and note any change in the *average* value of the readings.

(ii) Connect the output to an oscilloscope and see if the *amplitude* of the wave produced varies when the frequency is increased.

(A $1\ \mu\text{F}$ capacitor across the output will reduce the 'spikes' on the waveform.)

The Opposition

Resistance (R)

In direct current circuits the only opposition to the flow of charge is *resistance*. A capacitor acts as a complete block to d.c. and a coil or inductor behaves like any other resistor once the current is steady. The component offering opposition to the flow of charge is called a *resistor* and its property *resistance*. The opposition to the flow of charge is measured by the ratio $\frac{V}{I}$ and this is also labelled *resistance*.

Whenever current flows through a resistor heat is produced. Electrical energy has been transformed to heat energy. It is this ability to change electrical energy into heat, rather than the opposition to the flow of current, which enables us to identify resistance in an a.c. circuit.

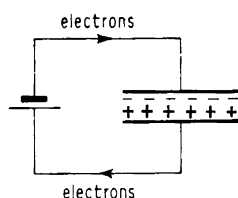


Fig. 286

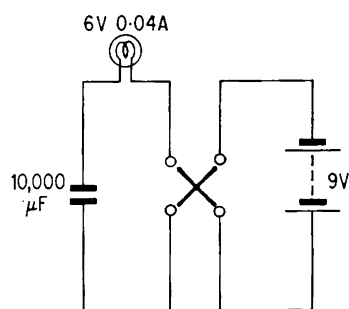


Fig. 287

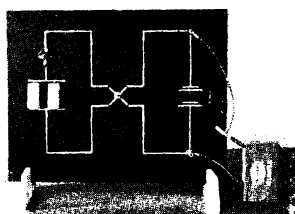


Fig. 288

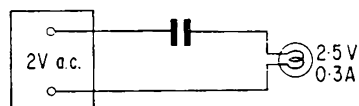


Fig. 289

Capacitance (C)

When a capacitor is connected to a dry cell, electrons flow *to* one plate and *away from* the other. One plate becomes negatively charged and the other positively charged (Fig. 286). The greater the capacitance, the greater the charge that can be stored.

We define the thermal capacity of a body as the quantity of heat needed to change its temperature by 1 degree. Electrical capacity, or rather *capacitance*, is the quantity of electricity needed to change the potential difference by 1 volt.

$$C = \frac{Q}{V}$$

farads coulombs
volts

Capacitance depends on the area of overlap of the plates, the distance between the plates, and the material between the plates. Air, waxed paper or ceramic materials are used as dielectrics in small capacitors and a layer of oxide or gas forms the dielectric of large electrolytic capacitors. Electrolytic capacitors should not normally be used with alternating currents. In the following experiments, however, we will use very small alternating voltages applied to capacitors which are rated at much higher working voltages. Under those conditions the capacitor should not be used for more than a few seconds at a time.

Experiment 8.22. Charge a 2000 μF capacitor with a 9V battery and discharge it through a 2.5V 0.3A lamp or a small electric motor. Does the capacitor store (a) charge (b) energy?

Demonstration 8.23. Fix a reversing switch in the circuit shown in Fig. 287. See if the bulb can be lit continuously by throwing the switch back and forth at different speeds. Does this mean that d.c. flows through a capacitor? Explain what is happening.

Experiment 8.24. Use the 2V a.c. output from the low voltage power unit to supply a 2.5V 0.3A bulb via a capacitor₁₄ (Fig. 289).

(i) Try capacitors of 100 μF , 250 μF and finally 2000 μF in the circuit, and state which offers most and which least opposition to the flow of charge.

(ii) Connect the 100 μF and 250 μF in parallel and say whether the opposition is greater or less than with either of these alone.

(iii) Wire the 2000 μF and 250 μF in series and comment on the result produced.

Complete the following statements.

The greater the capacitance the . . . the opposition to flow.

Capacitors in parallel offer . . . opposition to flow than one capacitor.

Capacitors in parallel must therefore have a . . . capacitance than a single capacitor.

Capacitors in series offer . . . opposition to flow than one capacitor.

Capacitors in series must therefore have a . . . capacitance than a single capacitor.

In a capacitor the opposition to flow is called the reactance (X) or, more correctly, *capacitive reactance* (X_C). It is measured by the ratio of the applied voltage (V) to the current (I).

$$X_C = \frac{V}{I}$$

ohms volts
amperes

Inductance (L)

You have already discovered that it takes longer for a direct current to build up to its maximum value in a coil than in a carbon resistor (page 74, Fig. 160). Apparently the coil resists changes in the current. In the following experiment you can investigate the behaviour of a coil in an alternating current circuit.

Experiment 8.25. Take a 6 metre length of 26 gauge wire and connect it to a torch bulb and a 2V a.c. supply. Wind a few turns on one limb of a C-core and note any difference. Join a second C-core to the first to complete the magnetic circuit (Fig. 290). Does this affect the brightness of the lamp?

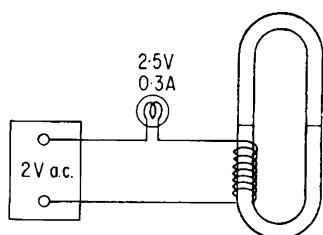


Fig. 290

Repeat this procedure with more and more turns added until there are about 60 turns on the core. What results are produced? On what factors does opposition to flow depend?

You have just built an *inductor* or *choke*. The opposition to a.c. in it is clearly due not only to the resistance of the wire. It depends also on the opposing e.m.f. induced in the coil by the changing magnetic field. The greater the changing magnetic flux through the coil, the greater the opposition. We call this opposition *inductive reactance* (X_L).

For a *pure* reactance the inductive reactance is given by the ratio of the applied voltage (V) to the current (I).

$$X_L = \frac{V}{I}$$

ohms volts
amperes

Impedance (Z)

The total opposition to the flow of alternating current in a circuit is called the *impedance* (Z). Impedance is due to resistance and/or capacitive reactance and/or inductive reactance.

Property of Component	Component which has this property	Opposition to a.c. $\left(Z = \frac{V}{I}\right)$
resistance (R) capacitance (C) inductance (L)	resistor capacitor inductor	resistance (R) capacitive reactance (X_C) inductive reactance (X_L)

Impedance and Frequency

In the following experiments you can investigate any changes in the impedance of various components as a result of a change in the frequency of the supply. By using the slow a.c. generator a *constant supply voltage* can be obtained at different frequencies. *Is this true for the output of an alternator such as a bicycle dynamo?* (23) *Explain your answer* (24).

Experiment 8.26

(i) Connect a 6 volt battery to the input terminals of a slow a.c. generator N_{170} and wire the output terminals to a 600 ohm resistor and a 10 mA a.c. ammeter (Fig. 291). How does the average current depend on the frequency? How does the impedance (in this case resistance) of this circuit vary with frequency?

(ii) Replace the resistor by a $100\ \mu\text{F}$ capacitor and repeat the experiment. How does the average current vary when the frequency is increased? How does the impedance (in this case capacitive reactance) vary when the frequency increases?

(iii) Replace the capacitor with a 5000-turn coil₁₀ (LB-3) and see how frequency affects the current. Does the impedance (inductive reactance) of a coil increase or decrease as the frequency increases?

Complete the following statements.

Resistance (R) . . . with increase of frequency.

Capacitive reactance (X_C) . . . with increase of frequency.

Inductive reactance (X_L) . . . with increase of frequency.

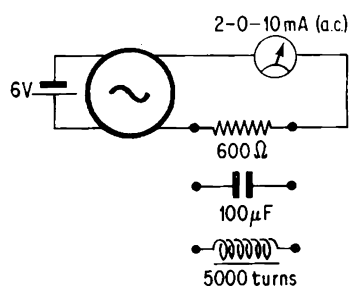


Fig. 291

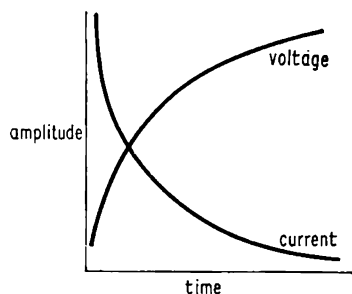


Fig. 292

Capacitive Reactance

Demonstration 8.27. Have another look at the apparatus illustrated in Fig. 58 (a), and investigate the changes of current and voltage.

When a capacitor is being charged up, the charging current falls rapidly as the voltage across the capacitor increases (Fig. 292). Opposition to the charging current in a capacitor, then, depends on the voltage across the capacitor due to its charge. *Can you now explain why the reactance of a capacitor should be less at higher frequencies?* (25) (*Hint: How does the frequency affect the charging time?*)

Inductive Reactance

The induced e.m.f. in a coil depends on the rate of change of magnetic flux (page 67). The induced e.m.f. in an inductor must also depend on the rate at which the magnetic field is changing. If the frequency of an alternating current through a coil increases, the rate of change of the magnetic field must also increase. *What will then happen to the induced (back) e.m.f.?* (26) *Is this likely to increase or reduce the current?* (27) *Does this agree with your experimental results?* (28)

Resistance, Capacitance and Inductance

The results of these experiments may be summarised by considering the circuit in Fig. 293, in which a reversing switch connects

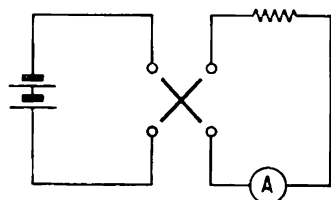


Fig. 293

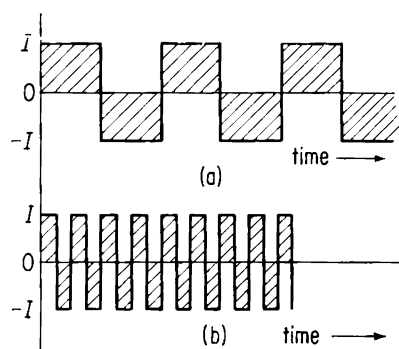


Fig. 294

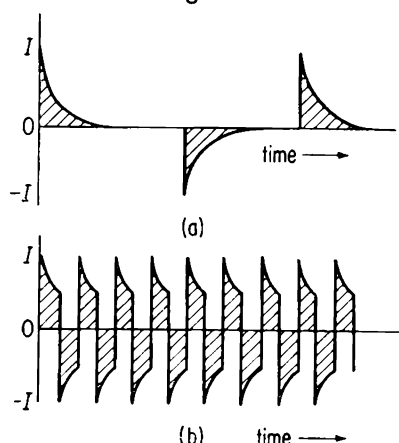


Fig. 295

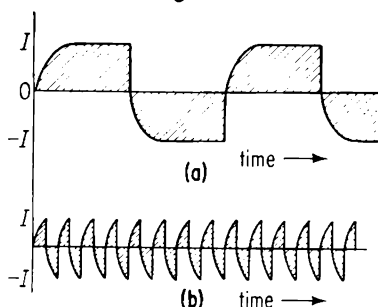


Fig. 296

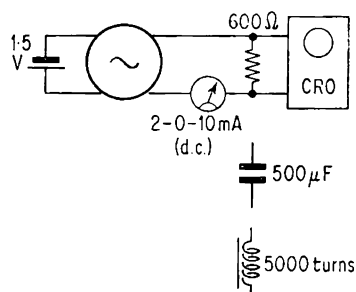


Fig. 297

a battery to a resistor and meter. If the voltage is switched slowly (low frequency) the current will be as shown in Fig. 294 (a). When switched more quickly (high frequency) it will be as shown in Fig. 294 (b). The shaded areas indicate the effective current. This current is the same at all frequencies.

If now the resistor in Fig. 293 is replaced by a capacitor, the current at low switching frequencies will be as shown in Fig. 295 (a) and at high frequencies it will be as shown in Fig. 295 (b). At high switching frequencies the current is never allowed to fall to a low value and so the effective current is greater at high frequencies.

If an inductor is inserted in the circuit of Fig. 293 in place of the resistor, the current at low frequencies will be as shown in Fig. 296 (a). At high switching frequencies the current does not have time to build up to its maximum value before the switch reverses the supply and so the effective current, shown in Fig. 296 (b), is much smaller.

Optional Extras

Lissajou's Figures

Demonstration 8.28. If the X and Y plates of an S51E oscilloscope are connected to two separate a.c. supplies, of which only one frequency is known, the unknown frequency can be found from the shape of the figures if a stationary pattern is produced. (Lissajou's figures.) Draw figures for the following frequency ratios—1 : 1, 1 : 2, 1 : 3, 2 : 1.

Out of Step

When dealing with d.c. circuits, we did not have to consider whether or not the current and the voltage were in step as they both had steady values. Current and voltage are changing continuously in alternating current, and so we ought at least to ask whether or not these two quantities are always in step. When a p.d. is applied to a coil, does the charge flow immediately? Does the current reach its maximum at exactly the same instant as the voltage applied? The following experiments should help you to answer these and other similar questions.

Experiment 8.29

(i) Use a 1.5 volt cell as the input to the slow a.c. generator and connect the a.c. output to a 600 ohm resistor and a 2-0-10 mA (or centre zero) meter (Fig. 297). Take wires from either side of the resistor to the input of a C.R.O. Fig. 298 shows a suitable arrangement with the meter needle pointing to the spot in the centre of the screen, when no current flows through the resistor. Use the C.R.O. with its time base switched off as a voltage indicator, and slowly turn the generator handle to see if the current and voltage are in step (in phase). Are they?

(ii) Replace the resistor with a 500 μF capacitor₁₄ and repeat the experiment. Are current and voltage in phase now? If not, which reaches its maximum value slightly before the other? We

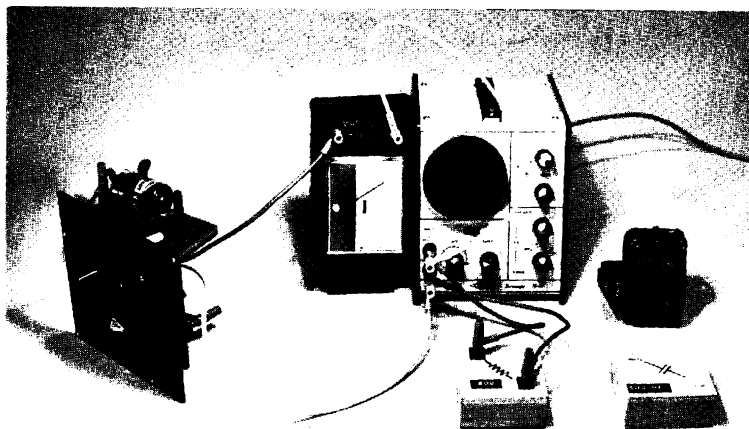


Fig. 298

say that the one *leads* the other. One revolution of the generator wheel represents a complete (360°) cycle. Can you estimate the angle between the positions where the current and the voltage reach their maxima? Can you explain in terms of flow of charge why there should be this phase difference?

Complete the statement

In a capacitor the current . . . the voltage by . . . $^\circ$.

(iii) Now insert a 5000-turn coil₁₀ in place of the capacitor and note any difference. Why is this? Does the voltage or current reach its maximum first? Which is *leading*? What is the approximate angle this time?

Complete the following statement

In an inductor the current . . . the voltage by approximately . . . $^\circ$.

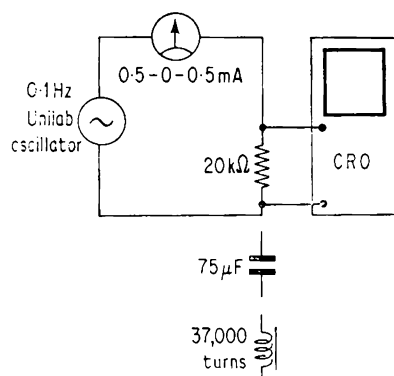


Fig. 299

Leading and Lagging

The circuit shown in Fig. 58 (a) (page 31) showed that the voltage across a capacitor increased as the rate of flow of charge into it decreased. A voltage developed across the capacitor *after* the current had charged it. That is, the voltage 'lagged' behind the current.

The apparatus shown in Fig. 160 (page 74) showed that the current through an inductor built up more slowly than the current through a resistor. The current in the inductor 'lagged' behind the applied voltage owing to the back e.m.f. developed by the rising current. The following experiments provide alternative demonstrations of these effects.

Demonstration 8.30

(i) Use the Unilab 0.1 Hertz oscillator, a 0.5-0-0.5 mA meter and a C.R.O. to compare the current through a 20 kilohm resistor with the voltage across it (Figs. 299 and 300).

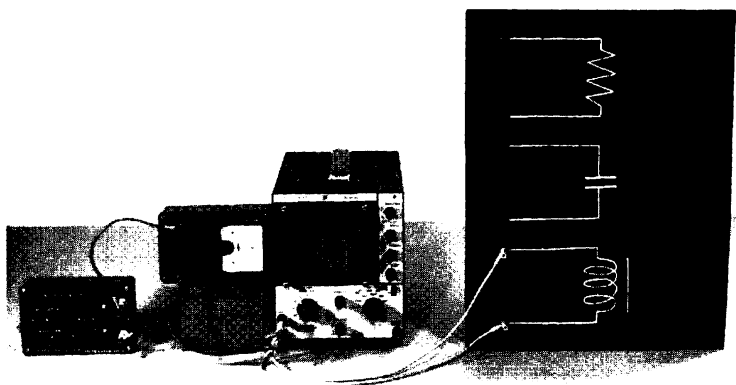


Fig. 300

Repeat this experiment with a $75\ \mu\text{F}$ capacitor and then a $37,000$ -turn coil on a large C-core₁₀.

(ii) An alternative arrangement, using a motor driven slow a.c. generator₁₇₀ and interscale meters₂₈, is illustrated in Fig. 301. A $3.3\ \text{k}\Omega$ resistor, $500\ \mu\text{F}$ capacitor and $12,000$ -turn coil are suitable



Fig. 301. From the Esso film 'The Oscilloscope and Slow A.C.'

Demonstration 8.31. A double beam oscilloscope can be used with the circuit shown to illustrate phase difference between resistive, inductive and capacitive circuits.

(Note. With some oscilloscopes this circuit will introduce a 180° phase shift between the two traces.)

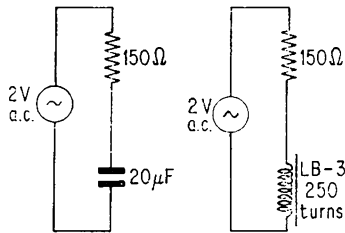


Fig. 303

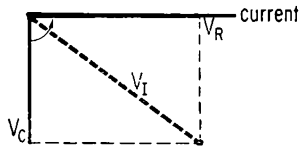


Fig. 304

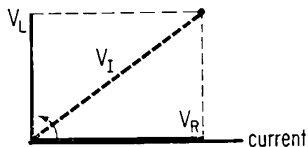


Fig. 305

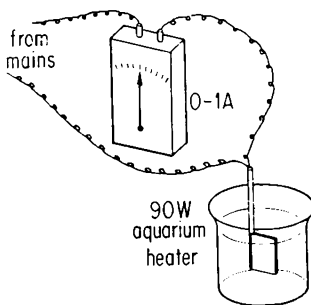


Fig. 306

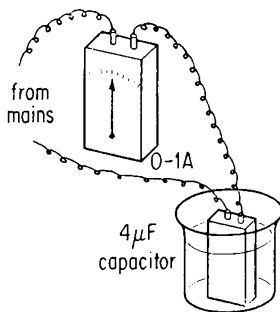


Fig. 307

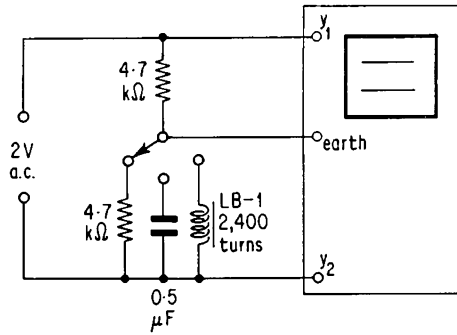


Fig. 302

Phasors

Experiment 8.32

(i) Calibrate a Serviscope Minor C.R.O., using the 1 volt a.c. output from the low voltage power supply. With the circuits shown (Fig. 303) use the calibrated C.R.O. to measure the input voltage and the voltages across R , C and L . What do you conclude?

(ii) You can use vectors (or phasors as they are more properly called) to represent the three voltages in each circuit. Use a phasor diagram to represent the voltage across the resistor V_R , the capacitor V_C and the resultant or input voltage V_I (Fig. 304).

(iii) Now draw a diagram to represent the voltage across the resistor V_R , the inductor (assume pure) V_L , and the input voltage V_I (Fig. 305). Explain why the calculated value of V_I differs from the measured value.

(iv) Finally connect the coil and capacitor in series, with no resistance in the circuit other than the resistance of the coil, and repeat the experiment. Explain your results.

Power

Demonstration 8.33. Connect a 90 W aquarium heater to the mains via an 0–1 A a.c. meter. Insert the heater in a beaker of water (Fig. 306). Now connect a $4\ \mu\text{F}$ capacitor in a similar circuit and insert it in a similar beaker of water. Switch on both circuits at the same time and compare the rate at which the water is heated in the two beakers.

It is clear from the last experiment that the amount of energy taken from the mains is quite different in a capacitor and a resistor, although the voltage and the current are nearly the same in each case. Before we continue our study of power in a.c. circuits, consider the following analogy.

Suppose that as a truck is moving along a railway line at two metres per second you exert a force of 50 newtons on the side of the truck. You are pushing at right angles to the direction in which the truck is moving. *At what rate are you supplying energy to the truck; that is, what is your power?* (29) *Why can the simple product of force times speed not be used here?* (30) Normally we might

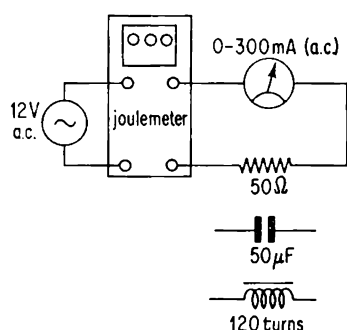


Fig. 308

expect an object to move in the direction in which we push it and in such a case the work done is the product of force and distance.

In d.c. circuits the current and voltage are steady and thus in phase. We can find the power by multiplying current and voltage together. As we have seen that current and voltage are not necessarily in phase in an a.c. circuit, we shall now investigate the power in various components.

Demonstration 8.34

(i) Connect a 12 volt transformer to a joulemeter, 50 ohm resistor and 0–300 mA (a.c.) meter as shown in Fig. 308. Switch on and note the current and speed at which the joulemeter disc is rotating. Find the energy transferred in (say) 100 seconds and record the results in the table below.

(ii) Replace the resistor by a $50\ \mu\text{F}$ capacitor and repeat the above procedure.

(iii) Finally use a 120-turn coil₁₀ (LB-2) on a double C-core in place of the capacitor.

(iv) Now calculate the product VIt and compare this with the energy transfer as recorded by the joulemeter.

	V	I	Energy transfer $V.I.t$ ($t = 100\text{s}$)	Joulemeter Readings during 100s
Resistor				
Capacitor				
Inductor				

As no heat is produced in a purely reactive circuit we cannot find the *power* from the product $V \times I$. Energy is transformed in an a.c. circuit only by resistance (that is, where voltage and current are in phase), so that it would be necessary to find the value of the voltage across the resistance in the circuit before the power could be calculated. This is not easy in practice, as all inductors have some resistance, and we therefore depend on our 'black box'—the joulemeter or kilowatt-hour meter—to measure the energy transformed.

The power *at any instant* can be found by multiplying the current and the voltage. In the following graphs this product is plotted in red. The shaded area represents the power being taken from the supply (above the line) and the power being fed into the source of supply (below the line).

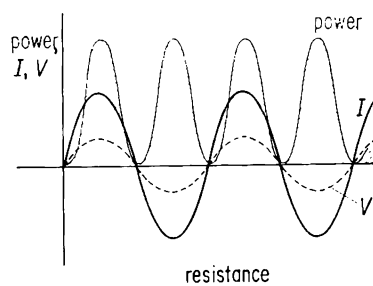


Fig. 309

Resistance

Power is always *positive* (Fig. 309); that is, energy is always being taken from the source and changed into heat.

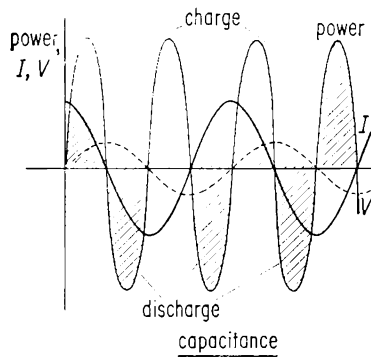


Fig. 310

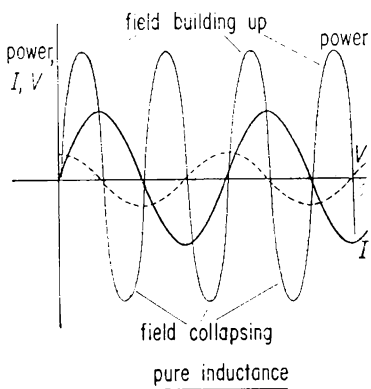


Fig. 311

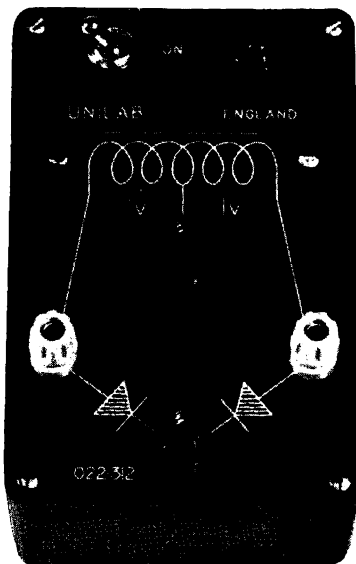


Fig. 313

Capacitance

Positive and negative half cycles of the power curve are equal. On the average *no* energy is being taken from the source. The energy taken from the source on each positive half-cycle is stored in the capacitor. This energy is returned to the source during the negative half cycle (Fig. 310).

Pure Inductance

Energy is stored in the magnetic field during the positive half cycle of the power curve and returned to the source of supply when the field collapses. On average *no* energy is taken from the source (Fig. 311).

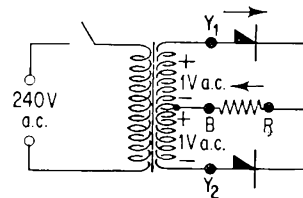


Fig. 312

Full wave Rectifiers

Using a transformer with a centre-tapped secondary (Fig. 312), you can join together two half-wave rectifiers to form a full-wave rectifier_{N104}. Each half is identical with the circuit shown in Fig. 283, but the rectifiers conduct on alternate half-cycles. *When the voltage across the secondary is as shown, which rectifier is conducting?* (31) *In what direction will electrons flow through the resistor?* (32) *If R and B are the d.c. output terminals, which is the positive terminal?* (33) *What will be the p.d. between Y₁ and Y₂?* (34)

Experiment 8.35. Connect a 600 ohm resistor to the d.c. terminals of a low voltage power supply (Fig. 313) and study the voltage waveform using a C.R.O. How does the waveform compare with that obtained with the half-wave rectifier? Explain the difference.

An indirectly heated double-diode rectifier is illustrated in Fig. 314. Compare this with the circuit of the low voltage power supply. *Can you suggest any disadvantages of the thermionic full-wave rectifier?* (35) *Is A or B the positive output terminal?* (36)

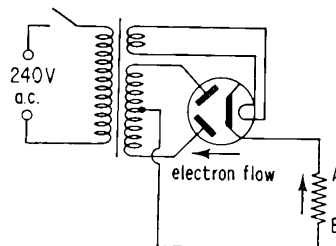


Fig. 314

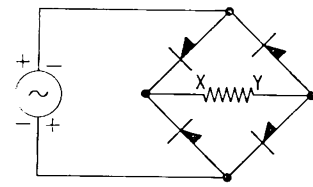


Fig. 315

Full-wave rectification is possible without a centre-tapped transformer, but four separate rectifiers, wired in a bridge circuit, are then required (Fig. 315). Such circuits are used with metal

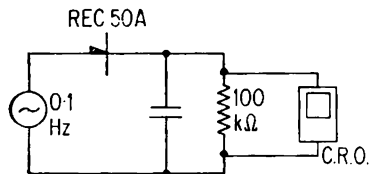


Fig. 316



Fig. 317

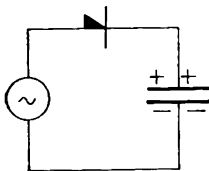


Fig. 318

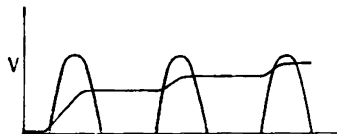


Fig. 319

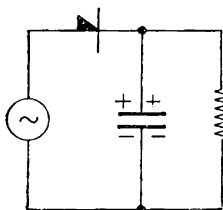


Fig. 320



Fig. 321

rectifiers in battery chargers, power packs and many types of electronic equipment. Bridge rectifiers are also fitted in multi-range meters in which a moving coil movement is used to read a.c. Can you suggest why thermionic valves are not often used in a bridge circuit? (37)

Trace the path of the electron flow or positive hole flow during both half cycles in the circuit shown; then state whether X or Y is the positive terminal (38).

Note that X is joined to similar rectifier terminals and Y to the opposite rectifier terminals.

Smoothing

In each of the above rectifiers the output is a fluctuating direct current. Such a current is quite adequate for some purposes, such as charging accumulators, but it is not at all suitable for radio sets and many other pieces of electronic equipment. In a radio set it would produce a loud 'mains hum' from the speaker. Fortunately it is fairly easy to iron out or *smooth* the bumps.

Experiment 8.36

(i) Using the circuit of Fig. 283 (page 113) connect a C.R.O. across the 600 ohm resistor and notice the waveform. Now connect a $2\ \mu\text{F}$ capacitor across the resistor. What difference does it make? Repeat this procedure with other capacitors ranging from $10\ \mu\text{F}$ – $2000\ \mu\text{F}$.

(ii) What happens to the waveform if the resistor is removed?

(iii) Compare the voltage waveforms across the resistor with a $50\ \mu\text{F}$ capacitor in parallel when they are supplied by (a) the above half-wave rectifier and (b) a full-wave rectifier (for example, using the 1 volt d.c. output of the power unit). You can do this by adjusting the gain control on the C.R.O. until the ripple amplitude from the half-wave rectifier is (say) two scale divisions and then noting the ripple amplitude from the full-wave rectifier. Which rectifier gives the smoother output? Why?

Demonstration 8.37. Use a Unilab 0.1 Hz oscillator and a S51E C.R.O. with long persistence tube to study the voltage across a 100 kilohm resistor alone and then in parallel with various capacitors ranging from $10\ \mu\text{F}$ to $2000\ \mu\text{F}$ (Fig. 316). Sketch the waveforms produced by a small and a large capacitor and explain the difference.

The voltage output from a half-wave rectifier is illustrated in Fig. 317. If, however, a capacitor is connected across the output (Fig. 318), it will be gradually charged up until the voltage across it reaches the peak value of the output. The voltage will then remain steady and no more charging current will flow (Fig. 319).

If a resistor (load) is now connected to the output (Fig. 320), the capacitor will be partially discharged through the resistor during the non-conducting half cycle. The voltage will therefore fluctuate as shown in Fig. 321. Can you suggest why (a) a larger capacitor and (b) the higher ripple frequency of the full-wave rectifier both produce better smoothing?

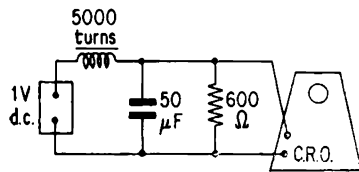


Fig. 322

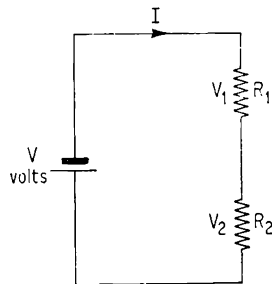


Fig. 323

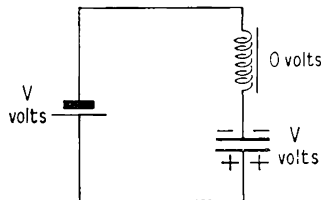


Fig. 324

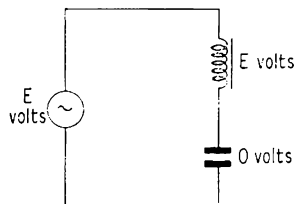


Fig. 325

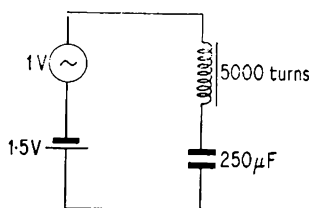


Fig. 326

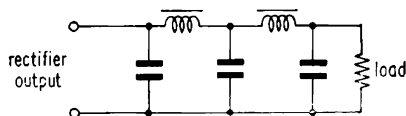


Fig. 327

Experiment 8.38. Connect the circuit shown in Fig. 322 to the 1 volt d.c. terminals of the low voltage supply_{N104}. Compare the output waveform with and without the core inserted in a 5000-turn Coil₁₀ (Unilab LB-3).

Potential Divider

When a voltage V is applied to two resistors in series (Fig. 323), it is divided into two parts so that $V_1 + V_2 = V$. If $R_1 = R_2$ then $V_1 = V_2$ and if R_1 is greater than R_2 then V_1 is greater than V_2 .

As the current I is the same through each resistor you can see from Ohm's Law that

$$I = \frac{V_1}{R_1} = \frac{V_2}{R_2}$$

hence

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

The voltage ratio is equal to the resistance ratio.

If now the two resistors are replaced by an inductor and a capacitor (Fig. 324), a charging current will flow until the capacitor is charged to the supply voltage. The resistance of the inductor is very low and the resistance of the capacitor very high, so that practically all of the supply voltage is developed across the capacitor.

If the d.c. supply is replaced by an a.c. supply (Fig. 325), we must consider the *reactance* of the components rather than the *resistance*. If we use a very large inductor and a very large capacitor, the reactance of the coil will be high and the reactance of the capacitor low, so that practically all the alternating voltage will be developed across the inductor.

Experiment 8.39

(i) Construct a combined a.c. and d.c. supply using the 1 volt a.c. output from a low voltage power unit and a 1.5 volt dry cell in the circuit shown in Fig. 326. Measure the alternating and the direct voltages across each component using a C.R.O. or suitable meter.

Across which component is the maximum (a) alternating, (b) direct voltage developed?

(ii) Repeat the experiment with (say) a 100 kilohm resistor across the capacitor. You have built a filter circuit in which the alternating and direct components present in the supply are separated out. Compare such a circuit with the one you used earlier (Fig. 322).

The output from a rectifier circuit contains both a.c. and d.c. components. It is the job of the smoothing circuit to filter these components so that as little a.c. ripple as possible is present across the load. Sometimes a series of capacitors and inductors is used as shown in Fig. 327.

Summary

Production

A.C. may be produced by a vibrating magnet near a conductor or a vibrating conductor in a magnetic field. A rotating magnet near a conductor or a conductor rotating in a magnetic field can also produce a.c.

Measurement

A.C. can be measured by

- (i) a moving-coil meter and rectifier,
- (ii) a moving iron meter,
- (iii) a hot-wire ammeter,
- (iv) a thermo-junction and moving coil meter.

Alternating voltages can be measured by a C.R.O. and by a moving-coil meter and rectifier.

Transformers

$$\frac{V_p}{V_s} = \frac{t_p}{t_s} \text{ approximately}$$

$$\frac{I_p}{I_s} = \frac{t_s}{t_p} \text{ approximately}$$

Capacitors

D.C. When the switch is closed the direct current reaches its maximum value immediately. As the charge builds up on the plates the size of the charging current decreases.

A.C. As the capacitance is increased the reactance decreases.
As the frequency is increased the reactance decreases.
The current leads the voltage by 90 degrees.

Inductors (pure)

D.C. When the switch is closed the current takes time to build up, owing to the inertial effect of the back e.m.f. induced by the changing magnetic field.

A.C. As the inductance is increased the reactance increases.
As the frequency is increased the reactance increases.
The current lags behind the voltage by 90 degrees.

Resistors

A.C. Resistance is not affected by frequency.
The current and the voltage are in phase.

Power

Electrical energy is transformed (to heat) only by the *resistive* component of an a.c. circuit.

Visual Aids

Charts: Principles of A.C. Generation₃₀ C893.

The Transformer₃₀ C771.

The Capacitor₃₀ C770.

Electricity in your Home₃₀ B301.

Filmstrips: Introduction to A.C.₄₃ CGA.B403.

8 mm Cassettes: The transformer₄₂ SP/E/11.

16 mm Films: A.C. and D.C.₃₁ DF.577.

Generating and Distributing Electricity₄₀.

A Picture of Power₃₉.

The Oscilloscope and Slow A.C.₃₇ (for teachers).

Oscillations

CHAPTER 9

A regular to and fro motion is called a vibration or oscillation. In an oscillatory system energy is continually changing from one form to another; for example, kinetic energy may change to potential energy then back to kinetic energy and so on. The number of to and fro movements every second is called the *frequency* (f) and the time taken for one such movement is called the *period* (T). We will measure frequency in vibrations per second, cycles per second or hertz (Hz) and the period in seconds (s).

$$f = \frac{1}{T}$$

hertz s

You have already met a number of vibratory systems, such as the simple pendulum and torsional pendulum (Book 1, page 120), the tuning fork, vibrating strings and air columns (Book 2, Chapter 5) the clock and ticker timer (Book 3, Chapter 1), vibrating trolleys and the wig-wag machine (Book 3, page 45). In all these systems the vibrations very quickly die down, that is, are *damped*, unless some energy is fed into them. This energy is needed to make up for three types of losses; internal friction, external friction and radiation.

1. Internal Friction

The ticker timer comes to rest almost immediately when the current is switched off. Energy is needed to bend the steel strip and some of this is changed to heat. As this is not recovered when the strip unbends the vibrations rapidly die down. Air resistance (external friction) and the radiation of sound waves also help to damp the vibrations.

2. External Friction

The vibrating trolleys (Book 3, page 45) quickly come to rest, partly because of external friction. The deformation of the springs (internal friction) and radiation of sound also reduce the amplitude of the vibrations.

3. Radiation

When a violin string is plucked some of the energy in the string is radiated as sound waves. Internal friction in the string and external friction in the form of air resistance also damp the oscillations.

In this chapter we will look at some examples of damped vibrations, maintained vibrations and the radiation produced by oscillatory systems.

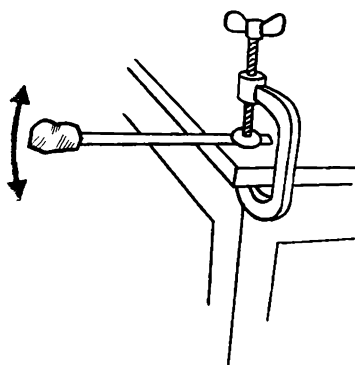


Fig. 328

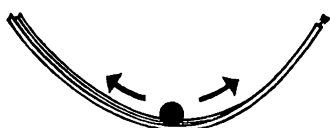


Fig. 329

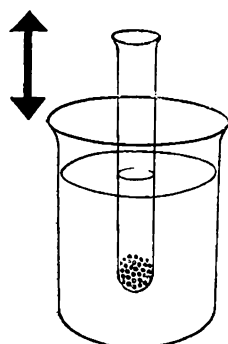


Fig. 330

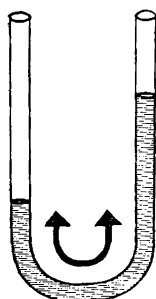


Fig. 331

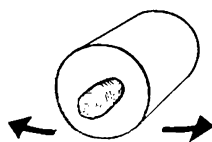


Fig. 332

Damped Vibrations

Experiment 9.1. As you investigate some of the following vibrating systems, ask yourself these questions about each.

1. What energy changes are taking place during vibration?
2. How can the frequency of vibration be altered? You should consider, for example, possible changes in the physical dimensions of the system, the mass, tension or elasticity where applicable. You might also like to see if the amplitude affects the natural frequency of vibration.
3. Can the damping of the system be reduced? If so, how?
4. Can you think of a simple way of feeding in energy to maintain the vibrations?

To measure the time of vibration and hence the frequency of a vibrator you might like to use such things as a stop watch, a hand stroboscope, a strobe lamp or calibrated C.R.O.

Vibrating Systems

- (a) A simple pendulum consists of a heavy bob, a length of thread and a rigid support.
- (b) A compound pendulum can be made from a metal bar or a metre stick pivoted at one end.
- (c) A flat metal strip (for example, a hacksaw blade) may be clamped to a bench (Fig. 328). Try this experiment with the blade vibrating vertically and horizontally with and without plasticine loading. Compare this system with the wig-wag machine.
- (d) A ball bearing will run to and fro in a bent curtain rail (Fig. 329).
- (e) A test tube loaded with (say) lead shot will vibrate up and down in water (Fig. 330).
- (f) A liquid oscillates to and fro in a U-tube (Fig. 331). Compare this with the water swishing to and fro in your bath!
- (g) A cylinder (for example, a tin can) loaded with plasticine will rock to and fro. Investigate the effect of altering the loading.
- (h) A stretched length of rubber tubing or coil spring with both ends firmly attached to a rigid support can be used to investigate the vibrations produced when the centre is plucked.
- (i) Pluck a sonometer wire (Fig. 333). How can the note produced be altered?

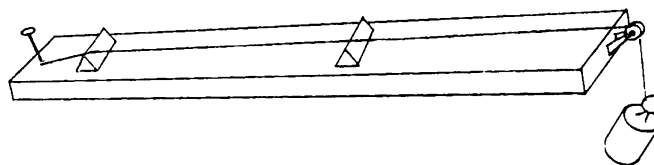


Fig. 333

Longitudinal Vibrations

- (j) Study the effect of passing a compression wave along a slinky resting on a smooth surface such as Formica. Hold both ends firmly as the wave moves to and fro (Fig. 334).

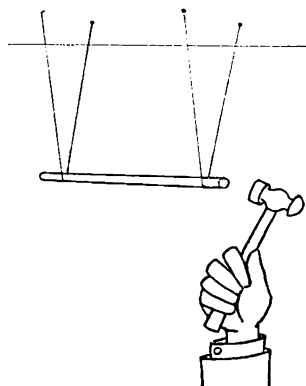


Fig. 335

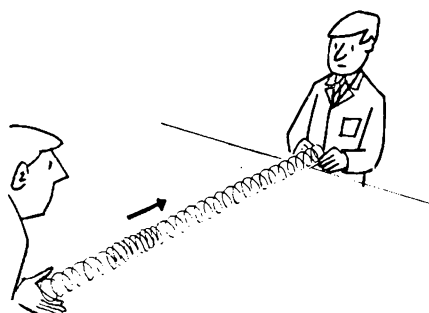


Fig. 334

(k) Give the end of a freely suspended iron bar a sharp tap (Fig. 335). Explain the results.

(l) Investigate the vibrations of one or more trolleys held by two springs N_{2A} (Book 3, page 45). Try several springs joined end to end.

(m) Repeat the last experiment with the trolley suspended by a very long length of string (Fig. 336). How does this affect the damping and the natural frequency?

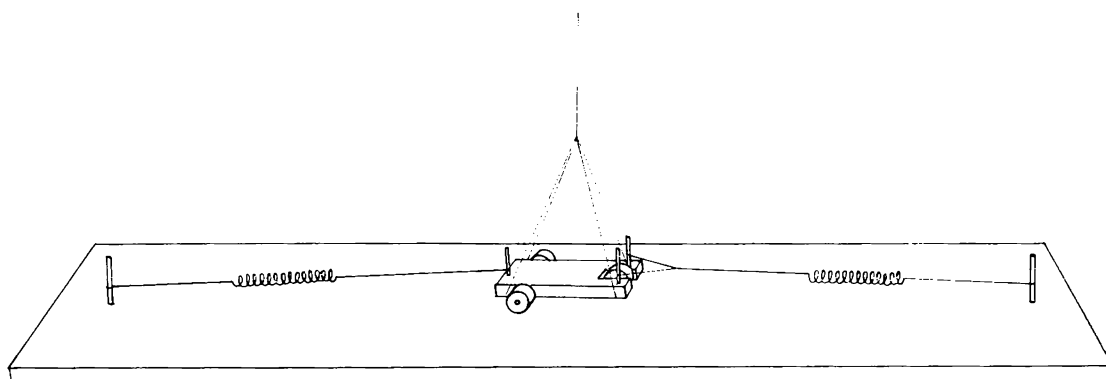


Fig. 336

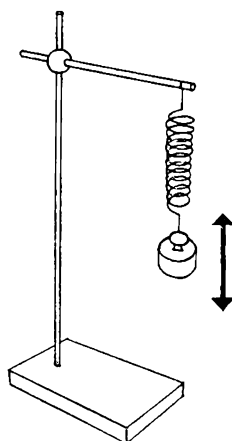


Fig. 337

(n) Attach a mass to a helical spring (Fig. 337) and allow it to vibrate up and down. Investigate the effects of changing the mass.

Torsional Vibrations

(o) A torsional pendulum can be constructed from a stout wire clamped at the top and supporting a metal block on its lower end. A dumb-bell is then attached to the block as shown in Fig. 338.

(p) Fig. 339 illustrates another type of vibrator in which a clock spring is attached to a revolving hardboard flywheel.

Problems

1. A small monkey is merrily swinging up and down on the end of a branch (Fig. 340). If a much heavier gorilla were in the same position, would it swing with the same frequency?

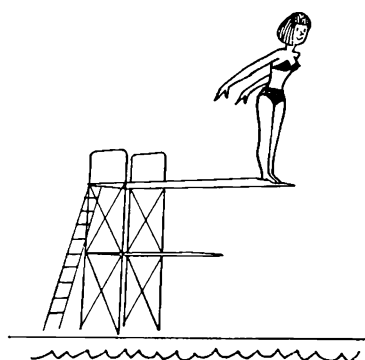


Fig. 341

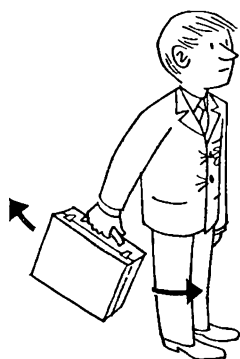


Fig. 342



Fig. 343

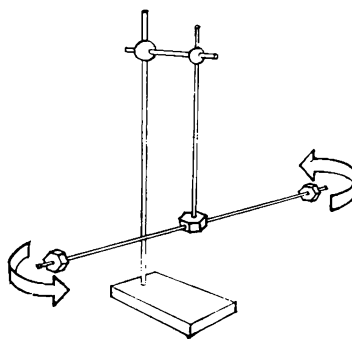


Fig. 338

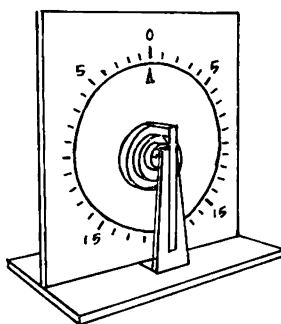


Fig. 339

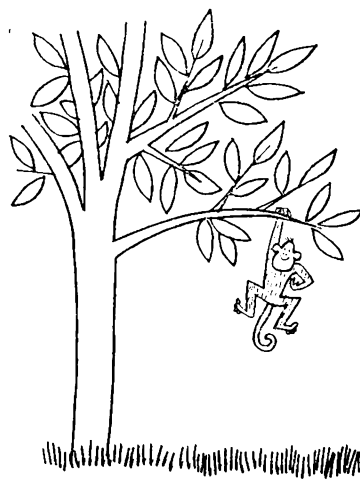


Fig. 340

2. A girl is bouncing up and down on the end of a springboard (Fig. 341). How could a stout man make the same springboard vibrate naturally at the same frequency?

3. A boy swings an empty suitcase to and fro at its natural frequency (Fig. 342). If the case were now filled with books, would the natural frequency be less, greater or the same as before?

4. You may have bounced up and down on your bedspring or on a trampoline (Fig. 343). Do you think the mass of the person jumping will affect his frequency?

Project 9.2. Set up the apparatus shown in Fig. 344 and explain the 'oscillations' of water out, air in, water out, etc.

Maintained Vibrations—Resonance

In some modern cars you can estimate the speed quite accurately by the noise of the various rattles (Fig. 345). For example, the off-side door might start around 30 miles per hour, the heater join in at 35 and the exhaust pipes up at 40. Can you explain this? (5)



Fig. 346

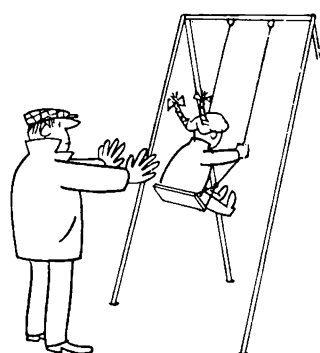


Fig. 347

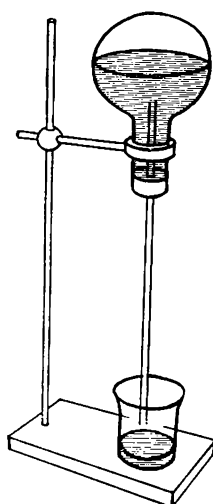


Fig. 344



Fig. 345

A boy is not tall enough to reach an apple on a tree. He can, however, make the branch swing with a large enough amplitude to enable his pal to reach the apple at the lowest point in the vibration (Fig. 346). *How must he pull the branch to accomplish this?* (6)

With what frequency would you push a child's swing to cause it to reach a large amplitude? (7) *Would any other frequency produce similar results?* (8)

When throwing a discus it is necessary to start by swinging the discus to and fro. *Can this be done at any frequency or is one particular frequency preferred?* (9) *Explain this.* (10)

The following experiments should enable you to answer the above questions.

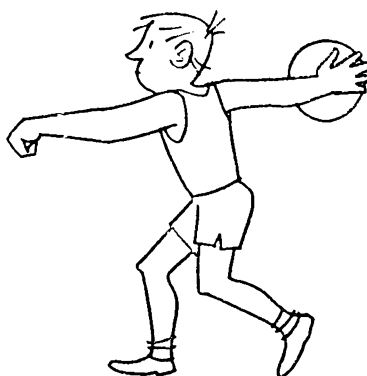


Fig. 348

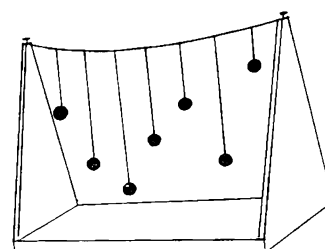


Fig. 349

Experiment 9.3. If the red ball is set swinging on the apparatus illustrated in Fig. 349, what happens? Why is this?

To maintain the swing of a pendulum it is necessary to feed in enough energy to make up for the losses due to friction. This energy must, however, be fed in at the right time; otherwise the

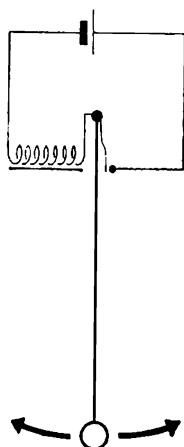


Fig. 350

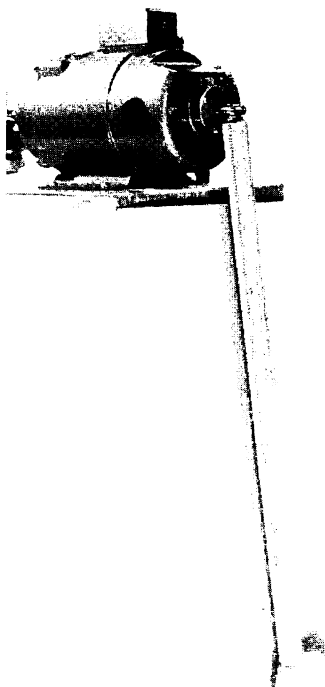


Fig. 352

vibrations will die down. Fig. 350 illustrates one way of doing this. The electromagnet pulls the iron pendulum to the left when the bob is over at the right hand side of its swing. Notice, however, that when the contact is first made, as the pendulum moves over to the right, the magnet will tend to slow the pendulum down. If the same current were flowing all the time, the retardation would be the same as the acceleration and the pendulum would eventually stop. *Can you explain why the circuit shown does maintain the pendulum swings, remembering that the current through a coil builds up as shown in Fig. 351?* (11)

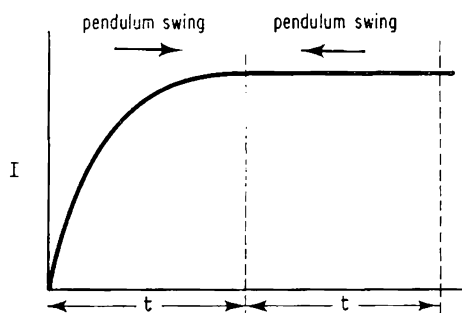


Fig. 351

Demonstration 9.4. Fig. 352 shows a primitive way of maintaining a pendulum in oscillation. The top of the pendulum is clipped to a slowly rotating motor driven shaft. The friction is sufficient to cause the pendulum to move through a small arc before slipping occurs and the pendulum swings back. Can you explain how such a system will maintain oscillation? To do this you may first have to investigate static friction and sliding friction.

(A small Terry clip, half meter stick and a mass of about 350 grammes of plasticine are suitable.)

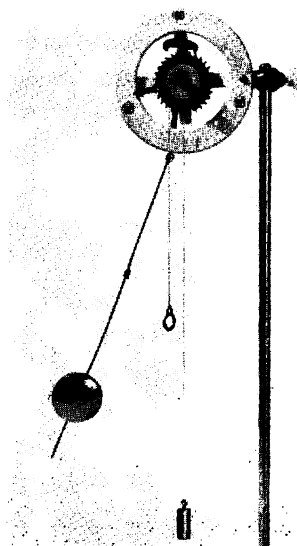


Fig. 353

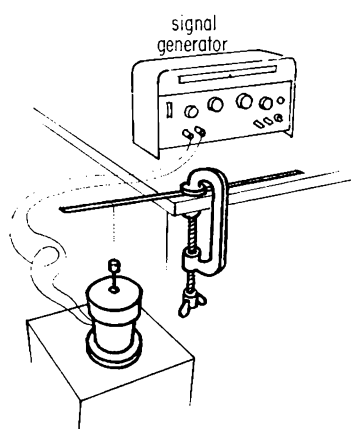


Fig. 354

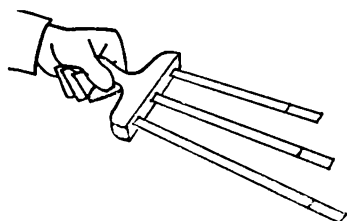


Fig. 355

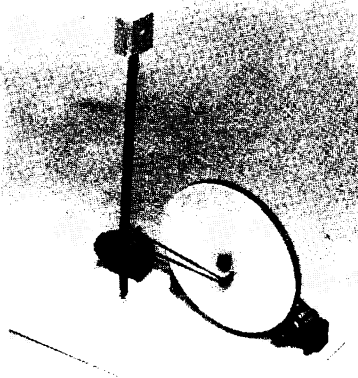


Fig. 358

The vibrations of a pendulum can also be maintained by a mechanical device called the anchor escapement. The escape wheel is driven by a clockwork motor or falling mass and provides the 'make-up' energy at the right moment. Perhaps you can work out its operation from Fig. 353, which illustrates an excellent Russian-built working model.

Experiment 9.5

(a) Connect an Advance vibrator₁₇ to a short length of hacksaw blade by means of an elastic band (Fig. 354). Vary the supply frequency and use a strobe lamp to find the frequency of the blade when maximum amplitude vibration is achieved. Compare this frequency with the natural frequency of the blade.

(b) Fig. 355 illustrates a manually operated alternative experiment using hacksaw blades of different lengths.

(c) Drill a hole in the centre of a 50 cm length of steel strip from a packing-case. Fix it to an Advance vibrator₁₇ supplied from a signal generator. Use a stroboscope to study the patterns produced at low frequencies.

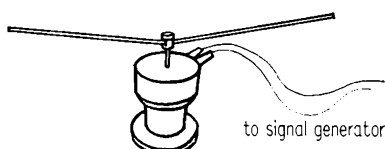


Fig. 356

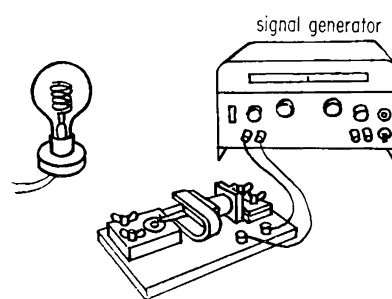


Fig. 357

(d) Connect the 5 ohm output of a signal generator to a ticker timer and note the amplitude as the frequency is varied. At what frequency is maximum amplitude observed?

Alter the length of the vibrator if necessary until it resonates at 50 Hz. This can be checked by illuminating the timer with a mains operated neon.

When the frequency of forced vibrations is equal to the natural frequency of the system, there is a vigorous response. This phenomenon is called *resonance*, and the frequency at which it occurs is called the *resonant frequency* (f_0).

Demonstration 9.6. A loaded hacksaw blade, mounted vertically, can be driven by a small electric motor geared down by means of a large wheel (Fig. 358). An elastic band should be used to connect

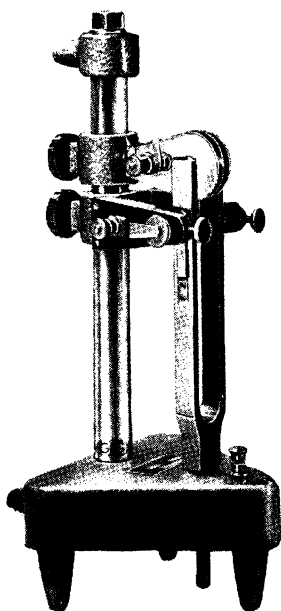


Fig. 359

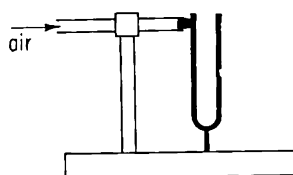


Fig. 360

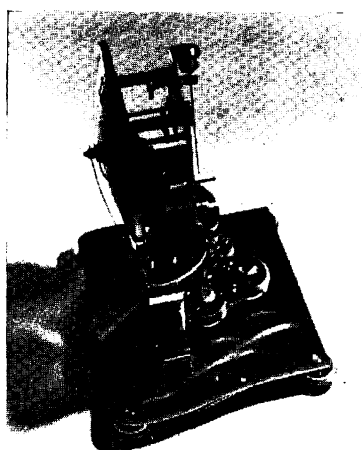


Fig. 362

the drive to the blade. Vary the speed of the motor and note when the maximum amplitude of vibration is obtained.

The vibrations of a tuning fork can be maintained electrically using the device illustrated in Fig. 359. Alternatively, a tiny air-blown piston can be used to feed in energy at the correct frequency (Fig. 360). The air pushes the piston and moves the tuning fork prong to the right. Once the piston has been moved right out of the cylinder air escapes at a high speed through the gap. This produces a low pressure region (cf. Book 2, page 11, Fig. 23) and the prong moves to the left again. In this way the tuning fork continues to vibrate at its natural frequency.

The vertical oscillations of a mass on the end of a helical spring can be used to control a Swiss clock (Fig. 361). Energy is fed in from a clockwork motor to maintain the oscillations.

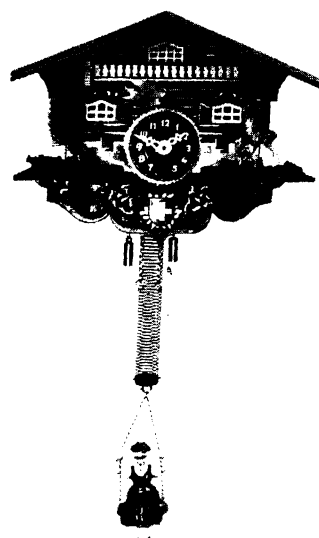


Fig. 361

Torsional Oscillations

We have seen that a clock may be controlled by a swinging pendulum or a mass vibrating up and down on a helical spring. A third method is illustrated in Fig. 362. In it two masses on either end of a short bar rotate to and fro. Energy is again fed into the system at the appropriate times from a wound spring or battery.

Demonstration 9.7. Torsional oscillation can be produced by a hardboard flywheel and a clock spring (Fig. 363).

(i) With the driving system stationary, displace the disc and then release it. Use a stop watch to find the period and then the natural frequency of oscillation.

(ii) Now use the electric motor to drive the oscillatory system. Vary the speed of the motor and note the amplitude of swing for each input frequency. Plot a graph showing how the amplitude of the oscillation varies with frequency or period.

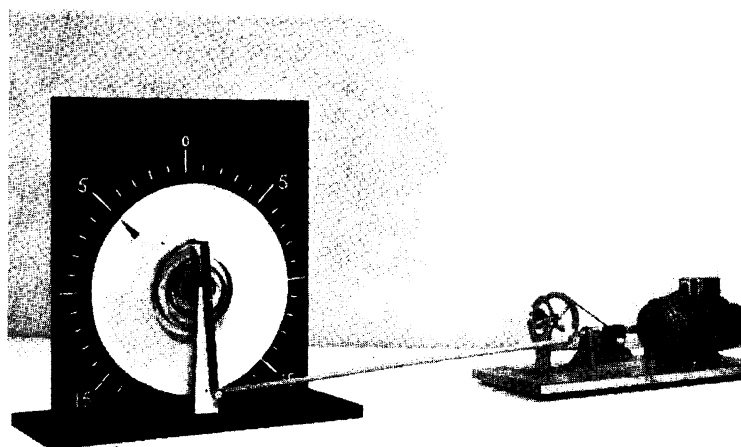


Fig. 363

Problem 12. Give examples of (a) a transverse travelling wave and (b) a transverse stationary wave, (c) a longitudinal travelling wave and (d) a longitudinal standing wave (cf. Book 2, Chapter 4).

Standing Waves

Demonstration 9.8—Transverse Vibrations

(a) Attach one end of a steel wire or nylon cord to a clamp and the other to a large polythene bottle of water (Fig. 364) or similar mass. The tension in the wire can be varied by altering the amount of water in the bottle. Connect the cord to an Advance vibrator directly or by means of an elastic thread and allow the cord to pass through a slide projector as shown. The amplitude of vibration may be measured on the projection on a blackboard.

See how the amplitude of a single 'loop' changes with frequency and plot a graph.

How does the tension of the wire affect the frequency at which maximum amplitude occurs? Does altering the length make any difference?

If the maximum amplitude of a single 'loop' occurs at a frequency f_0 (fundamental resonant frequency), what is the effect of driving the wire at frequencies $2f_0$, $3f_0$, $4f_0$, etc.?

(b) An alternative and much simpler arrangement is illustrated in Book 2, page 55. If white shirring elastic is used, impressive 'loops' are formed.

(c) The vibrations of a string may also be maintained with a bow. Can you see any similarity between playing a violin or cello and the method used to maintain oscillations in Demonstration 9.4?

(d) A number of dynamics trolleys joined by coil springs N_2A can be used in an effective demonstration of standing waves (Fig. 365). The apparatus is also useful for demonstrating travelling waves.

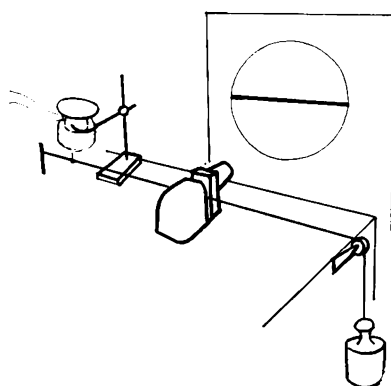


Fig. 364

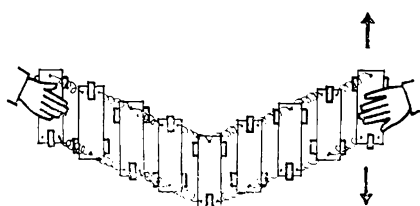


Fig. 365

Demonstration 9.9—Longitudinal Vibrations

(a) Paint a white mark every centimetre on a length of fine black elastic (Fig. 367). Attach one end of the elastic to a retort stand and the other to an Advance vibrator₁₇ fed from a low frequency generator.

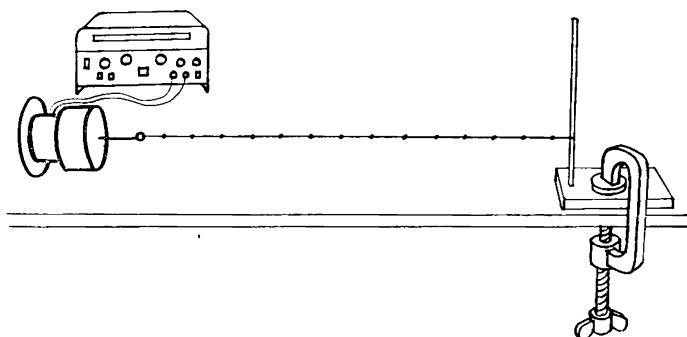


Fig. 366



Fig. 367



Fig. 368

Adjust the frequency until the centre mark appears to spread out to its maximum length (Fig. 368). Why is this?

Now double the frequency and make any fine adjustment needed to cause the centre white mark to appear stationary while marks a quarter and three-quarters way along the elastic appear to spread out. Explain this.

You may like to watch the elastic illuminated by a strobe lamp.

(b) The dynamics trolleys may again be used to show travelling and stationary longitudinal waves (Fig. 369).

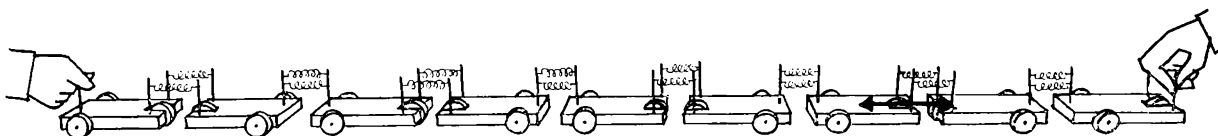


Fig. 369

Demonstration 9.10—Longitudinal Vibrations

(a) Feed a signal from an audio oscillator to a small loud-speaker or earphone placed near the end of a tube (Fig. 370). A microphone connected to an oscilloscope or valve voltmeter at the other end can be used to indicate the amplitude of the sound. Alter the frequency of the oscillator, and plot a graph showing how the sound amplitude varies with frequency. Investigate overtones.

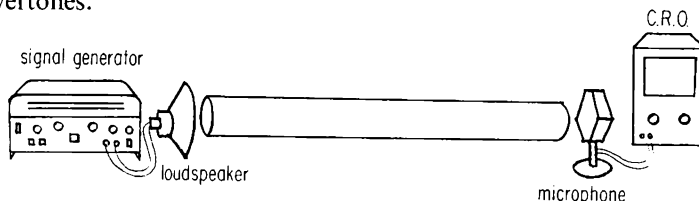


Fig. 370

(b) An alternative arrangement is shown in Book 2, page 70. An air column 20 centimetres long is suitable for a frequency range of 300–500 Hz.

The standing waves demonstrated in the last few experiments are produced by the interference of travelling waves before and after reflection (cf. Book 2, page 62). The points where the incident and reflected waves always cancel are called the *nodal points*.

Some of the energy which is fed into the system to maintain the standing waves is radiated by travelling waves of a different type. For example, the transverse standing waves in the vibrating wire produce travelling sound waves. The longitudinal standing waves in the tube do the same.

Practical Problem 13. Devise a method of maintaining oscillations in one of the following: (a) a vibrating hacksaw blade, (b) a helical spring pendulum, (c) a torsional pendulum, (d) a ball running to and fro on a curved rail.

Problem 14. Discuss energy changes in each of the following; (a) a torsional pendulum, (b) a guitar string, (c) a compound pendulum.

Problem 15. Why should a mains-operated ticker timer be tuned to a natural frequency of 50 Hz? If the length of the strip could not be altered, how could you reduce its natural frequency? Draw a rough graph showing how the amplitude of the vibration of a ticker timer varies with input frequency.

Problem 16. How is the frequency of a simple pendulum affected by (a) increasing the mass of the bob, (b) increasing the length of the string, (c) increasing the amplitude of swing from 5° to 10° ?

When has the bob its maximum (i) velocity, (ii) momentum, (iii) kinetic energy, (iv) potential energy, (v) acceleration? When has it zero acceleration?

Electrical Oscillations

In the mechanical oscillations which you studied, energy was continually being changed from one form to another. In Experiment 9.1 (p), for example, the kinetic energy in the rotating

flywheel was used to wind a spring. When the flywheel came to rest the energy was stored (P.E.) in the spring. The spring then unwound and lost its potential energy as the flywheel gained kinetic energy.

Can we find electrical components in which energy is stored (i) statically (potential energy), and (ii) as charges flow (kinetic energy)? Look at the following demonstration and compare it with Experiment 9.1 (p).

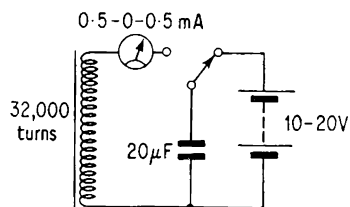


Fig. 371

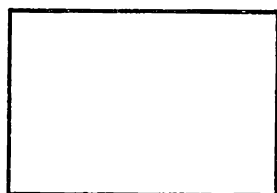


Fig. 373

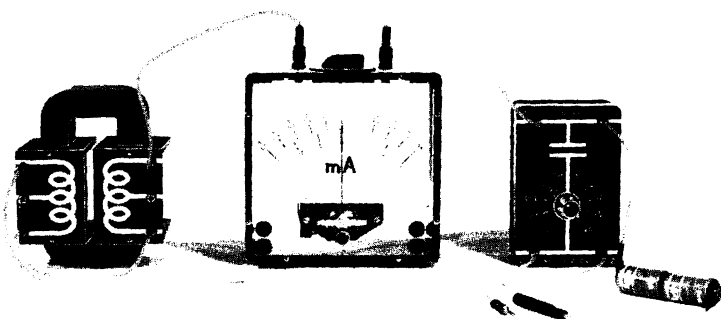


Fig. 372

Repeat the experiment with different values of capacitance (for example $1\ \mu\text{F}$ – $20\ \mu\text{F}$) and inductance (using 10,000–37,000 turns). Complete the following statements.

- (i) The frequency of oscillation increases when the capacitance is . . .
- (ii) The frequency of oscillation increases when the inductance is . . .

A coil and capacitor in parallel behave rather like the flywheel and spring (Fig. 339). When the capacitor is charged, electrical energy is stored in it. As the coil forms a conducting path across it, the capacitor discharges, causing a magnetic field to develop through the coil. When the magnetic field collapses, an e.m.f. is induced in the coil. This e.m.f. tends to keep the current flowing in the same direction, so that the capacitor is again charged up but with the opposite polarity. This to and fro movement of charge continues until all the energy has been transformed into heat and radiation.

Problem 17. Draw four diagrams to represent the intermediate stages of the process illustrated in Fig. 374.

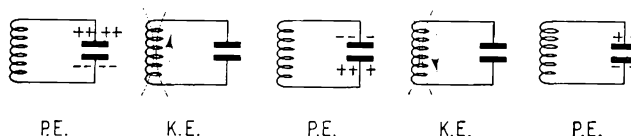


Fig. 374

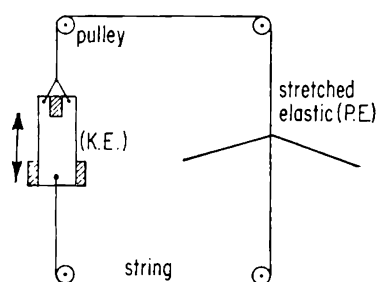


Fig. 375

Fig. 375 illustrates an analogy of a tuned circuit. Energy stored in the stretched elastic causes the trolley to move. When the elastic has lost all its potential energy the trolley is moving quickly. Its kinetic energy is then used to stretch the elastic in the opposite direction. The to and fro motion continues until all the energy has been transformed to heat and sound.

Demonstration 9.12. Damped oscillations can be produced by a 1200-turn coil and a $1\ \mu\text{F}$ capacitor in the circuit shown in Fig. 376. The time base circuit of the oscilloscope (S51E) is used to charge the capacitor once per sweep, thus enabling a 'stationary' pattern to be seen.

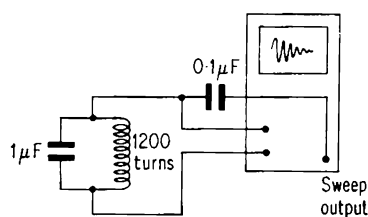


Fig. 376

Maintained Oscillations

In an electrical oscillatory circuit, energy is changed to heat as the current surges through the wires. Some energy is also radiated as electromagnetic waves. If oscillations are to be maintained at a constant amplitude, energy must be fed into the circuit at the correct frequency (cf. Demonstration 9.7). Here is one way of doing this.

Demonstration 9.13. With the apparatus used in Demonstration 9.11, connect the 2000-turn coil to the output of a low frequency a.c. generator N_{170} (Fig. 377). Note how varying the input frequency affects the amplitude of the current in the oscillatory circuit.

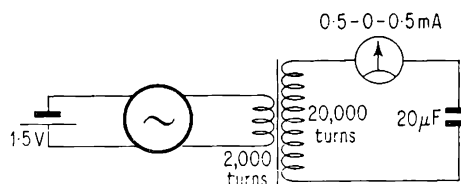


Fig. 377

Connect the oscilloscope across the capacitor, and note how the voltage across the circuit varies with changes of input frequency. At what input frequency is the voltage greatest? Does this correspond to the maximum current readings in the meter?

Although the above method can be used to maintain electrical oscillations, it is very clumsy and would be of little use at very high frequencies. If, however, energy could be fed from a battery at

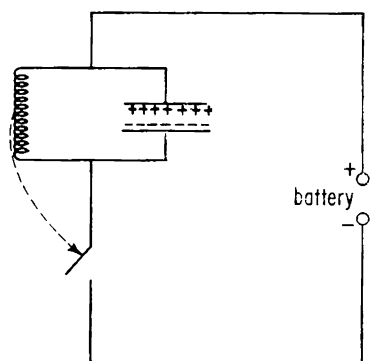


Fig. 378

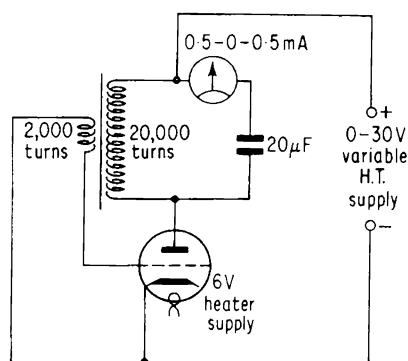


Fig. 379

just the right time during each oscillation, losses in the tuned circuit could be made up (Fig. 378). If a signal from the tuned circuit could be used to operate a switch at the appropriate moment, the oscillations could be maintained.

Fortunately a simple amplifier, such as a triode valve or transistor, can be used to supply the necessary energy automatically. In the oscillatory circuit in Demonstration 9.13 the 2000-turn coil can be used to control the 'make-up current' through a valve so that it is fed in at the right time.

Demonstration 9.14—(VLF)—Triode. Connect the oscillatory circuit to a triode valve₁₀ as shown in Fig. 379. When the H.T. supply is switched on, the current surges through the coil and the circuit starts to oscillate. The oscillations will, however, very quickly die out unless the anode current is made to fluctuate at the correct frequency and in the correct phase. The varying current in the large coil induces an e.m.f. in the small coil. This voltage is

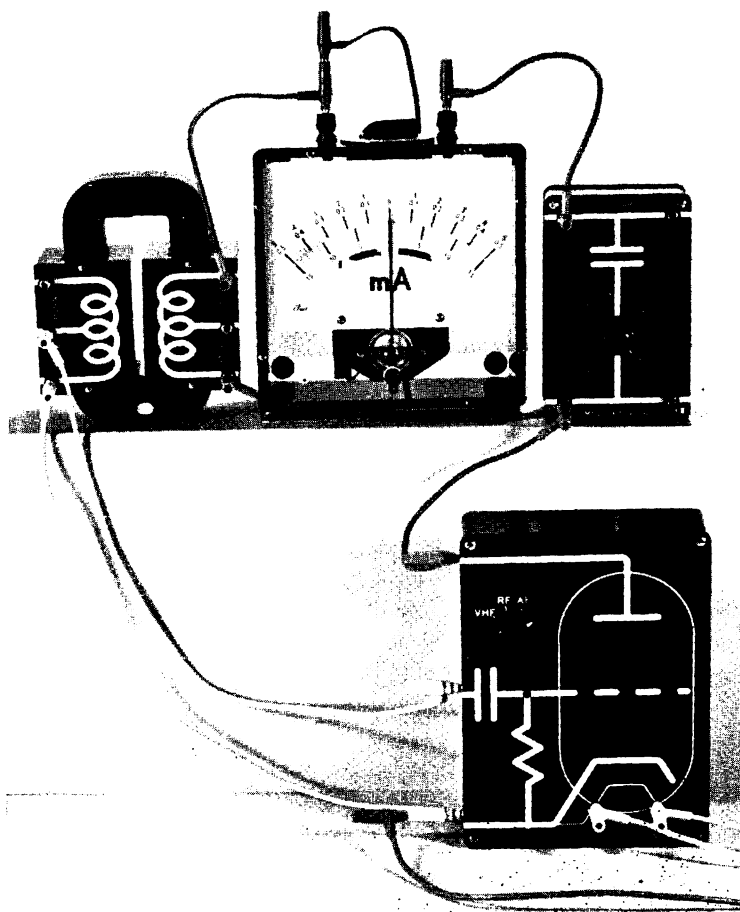


Fig. 380

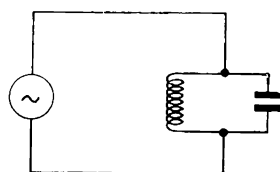


Fig. 381

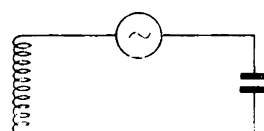


Fig. 382

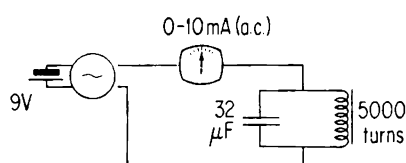


Fig. 383

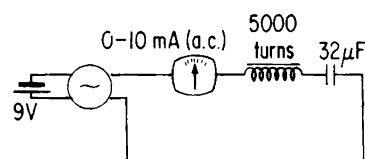


Fig. 384

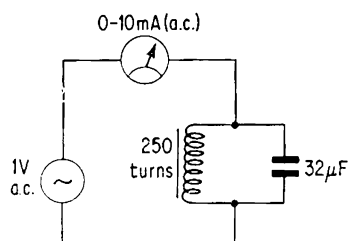


Fig. 385

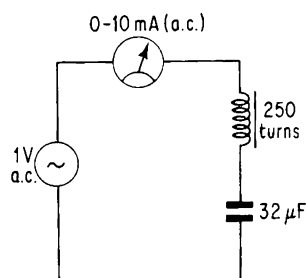


Fig. 386

applied to the grid of the valve and controls the anode current at the required frequency.

(i) Gradually increase the H.T. voltage until the circuit maintains oscillation. It may be necessary to reverse the connections to the 2000-turn coil to obtain the correct phasing. The wave form can be studied by connecting a C.R.O. across the capacitor. A C.R.O. with a long persistence tube is preferable.

(ii) Vary the value of the capacitor from $20\ \mu\text{F}$ to $1\ \mu\text{F}$ and note the effect on the oscillations.

(iii) Switch off the H.T. supply and observe the damped oscillations on the C.R.O.

Parallel and Series Circuits

When energy is fed into a tuned circuit as in Fig. 381, the circuit is called a parallel tuned circuit. If the supply is in series with the two components as in Fig. 382, the circuit is called a series tuned circuit. In the following experiments you should investigate the difference between these two circuits.

Experiment 9.15—Parallel Circuit. Use the low frequency a.c. generator N_{170} to supply a parallel circuit as shown in Fig. 383. A 5000-turn coil (LB-3), a $32\ \mu\text{F}$ capacitor and a 10 mA (a.c.) meter are suitable.

Vary the input frequency and note the current.

Experiment 9.16—Series Circuit. Use the same components as in Experiment 9.15 to investigate the current through a series circuit when the frequency changes.

Experiment 9.17—Parallel Circuit. Fix a 250-turn coil I_{10} (LB-3) on two C-cores (unclamped) and wire a $32\ \mu\text{F}$ capacitor in parallel with it. Connect these via a 10 mA (a.c.) meter to the one volt output of a low voltage power supply (Fig. 385). Make certain that the two parts of the C-core are firmly held together before switching on the supply.

Switch on and vary the inductance by gradually sliding one of the C-cores off the other, carefully watching the meter all the time. Do *not* allow it to go beyond full-scale deflection. State and explain what you observe.

Experiment 9.18—Series Circuit. Connect up the circuit shown in Fig. 386 and switch on. Gradually move one C-core relative to the other and note the change of current. Explain what you see.

Connect a C.R.O. across the coil and another across the capacitor, and watch the voltage across each as the inductance is varied. Compare these voltages at resonance with the input voltage.

From the results of these experiments complete the following statements.

- (i) In a parallel circuit at resonance the input current is . . .
- (ii) In a series circuit at resonance the input current is . . .

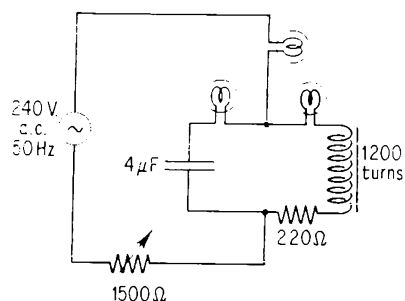


Fig. 388

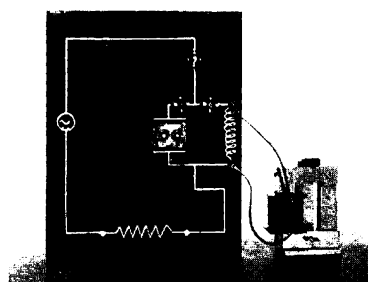


Fig. 389

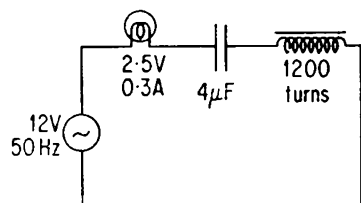


Fig. 390

Demonstration 9.19—Parallel Tuned Circuit

(a) An LB-4 coil, without a core, can be used in the circuit shown in Fig. 387. The low impedance output from a J₁ or SG65A signal generator₁₇ is suitable. The bulbs indicate the input current and the oscillatory current in the tuned circuits. Vary the frequency of the input and explain what is happening when the input current is minimum. When the bulbs in the tuned circuit are brighter than the other are we getting 'something for nothing'? Explain your answer.

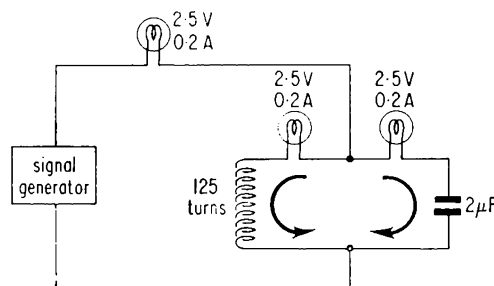


Fig. 387

What happens to the current through (i) the inductor, (ii) the capacitor at frequencies above and below resonance?

Alternating current meters may be used in place of bulbs in the circuit of Fig. 387 and a loudspeaker between the low impedance terminals of the signal generator will enable you to listen to the change in frequency.

(b) An alternative arrangement in which the resonant frequency of the tuned circuit is altered by sliding the choke₂ yoke is shown in Figs. 388 and 389. All the bulbs are 2.5V 0.3A.

Demonstration 9.20—Series Tuned Circuit

(a) Investigate the change of current in the circuit illustrated in Fig. 390 and Fig. 391 as the inductance is altered by sliding the yoke.

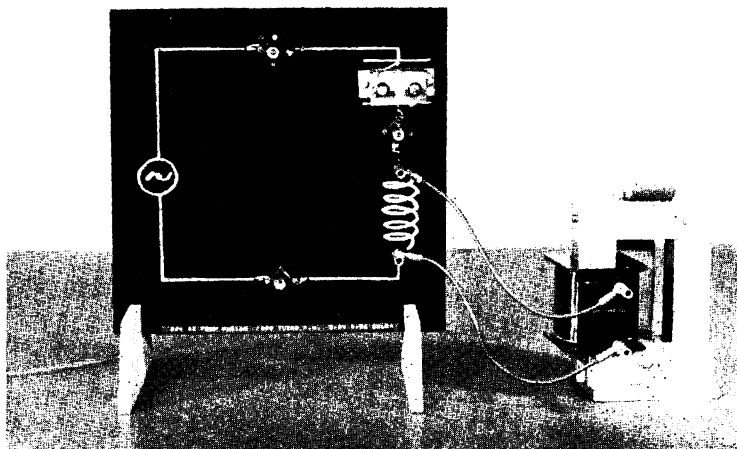


Fig. 391

(b) Using the circuit shown in Fig. 392 vary the frequency of the oscillator while you watch the current reading. Does it reach a maximum or minimum at the resonant frequency (f_0)? Compare the voltages across the inductor and capacitor at f_0 . How do these

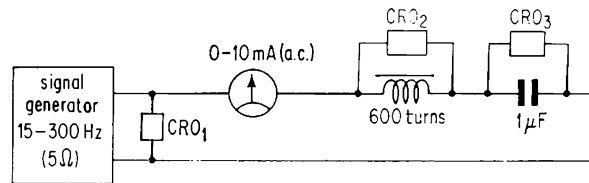


Fig. 392

voltages, as read on the C.R.O.s, compare with the input voltage? Across which component is the voltage greater (i) below f_0 and (ii) above f_0 ?

Plot a graph showing the variation of current with frequency.

(Warning: The C.R.O.s must not be fitted with an earthed terminal for this experiment. The Serviscope Minor and Advance OS12 are suitable.)

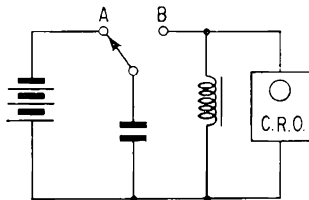


Fig. 393

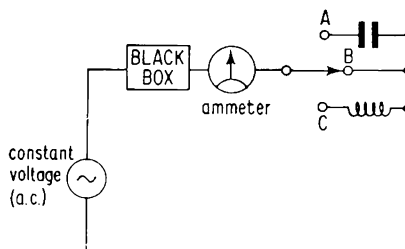


Fig. 394

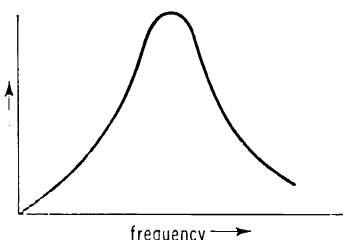


Fig. 395

Problems

18. Complete the following statements.

In a parallel tuned circuit

- at f_0 the current from the supply is at its . . . ,
- at f_0 the impedance of the circuit is at its . . . ,
- below f_0 . . . current goes through L than C ,
- above f_0 . . . current goes through L than C .

19. Complete the following statements.

In a series tuned circuit

- at f_0 the current is at its . . . ,
- at f_0 the voltages across L and C are at their . . . ,
- at f_0 the impedance of the circuit to the supply is . . . ,
- below f_0 the voltage across L is . . . than across C ,
- above f_0 the voltage across L is . . . than across C .

20. A large coil and capacitor are connected in the circuit shown in Fig. 393. If the C.R.O. has a long persistence tube, sketch the pattern produced when the switch is thrown to position B.

21. A constant voltage a.c. supply is connected to a 'black box' as shown in Fig. 394. When the switch is moved from B to A the current is reduced. When moved from B to C it increases. What could be in the black box?

22. Could Fig. 395 represent the variation of current or impedance in (a) a series, (b) a parallel circuit?

Optional Extras

Simple Harmonic Motion

Many of the vibrations you saw in the earlier experiments are similar to the vibrating mass on a helical spring.

Imagine a mass exerting a weight W on a helical spring as shown in Fig. 396. It is at rest opposite the zero mark on a scale. If the mass is pulled *downwards*, the force tending to restore it to its original position will be proportional to the displacement from the zero mark. If, on the other hand, the mass is raised *above* the zero position the force tending to pull it down will again be proportional to the displacement. In each case the restoring force is proportional to the displacement from the centre. The motion which results from such forces is called *Simple Harmonic Motion* (S.H.M.).

The following demonstrations suggest another way of looking at S.H.M.

Demonstration 9.21. Attach a table tennis ball to a gramophone turntable and use a compact light source_{N21} to project its shadow on to a mirror and then on to a ground glass screen (cf. Fig. 25, page 18). As the ball rotates, its projection can be seen moving up and down on the screen (Fig. 397). Set the ball in the central

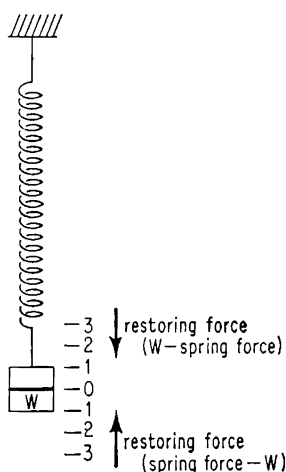


Fig. 396

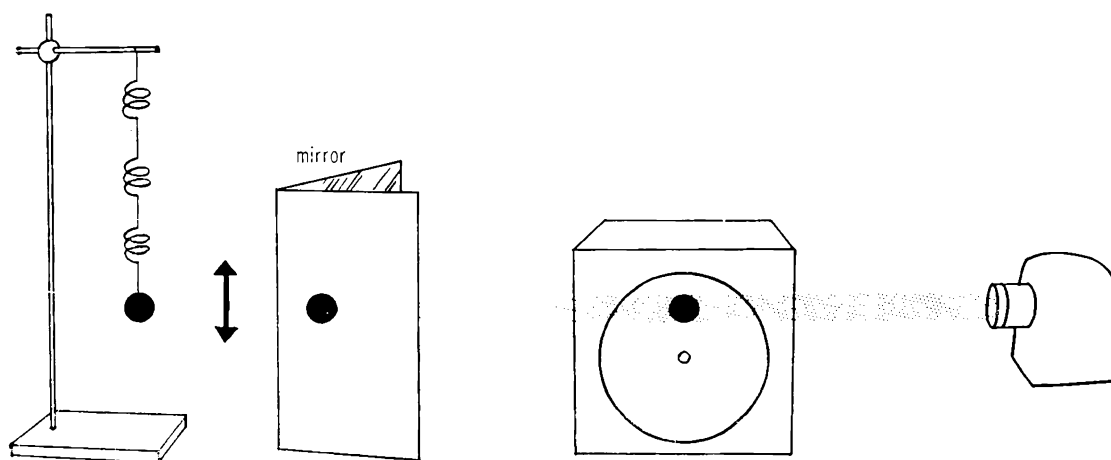


Fig. 397

position shown, and beside the projection of the ball hang a mass on a helical spring (three small springs_{N2A} in series and a mass of 575g oscillate at about 33 r.p.m.).

Start the turntable motor and alter the mass (for example, by adding plasticine) until it keeps in step with the projection of the ball.

The Sine Curve

The last demonstration showed that the *projection* of an object moving uniformly in a circle moves with S.H.M.

Imagine a distant point source of light beyond the left hand side of the page projecting on YY' the shadow of a particle as it moves

round in a circle (Fig. 398). When the particle is at A the projection is A' , at B the projection is B' etc. According to the results of the last demonstration the projection of the particle along YY' moves in S.H.M.

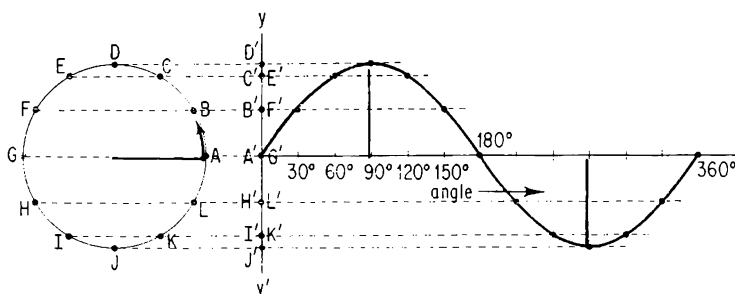


Fig. 398

If now we take YY as the Y axis of a graph on which is represented the displacement of the projected particle, and if we represent the angle through which the particle has rotated on the X axis, we obtain the curve shown. It is a *sine curve*.

As the particle must move at a uniform speed in a circle for the projection to move in S.H.M., the angle through which it rotates is proportional to time. The X axis of the graph could therefore represent time in seconds. The graph of the displacement of a body moving in S.H.M. plotted against time is therefore a sine curve.

You might now like to have another look at the machine illustrated in Fig. 203, page 87. Alternatively, look at the trace produced by an inked brush mounted on a vibrating steel strip (for example on a Fletcher's trolley) as a length of paper is pulled at a constant speed under it.

Oscillators

Demonstration 9.22. (VLF)—*Transistor*. The coil used in Demonstration 9.14 is suitable for this experiment. Use the 2000- and 15,000-turn coil as shown in Fig. 399. To start oscillations switch to position A when the capacitor will be charged in the polarity shown. Then switch to B . The capacitor will be discharged as electrons flow in the direction indicated. During this

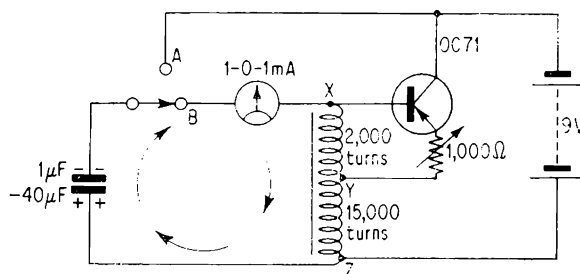


Fig. 399

time X will be negative with respect to Y , so that the transistor will conduct, causing more electrons to flow down through YZ .

In this way the necessary make up current is automatically fed into the circuit at the right time to maintain oscillation.

Connect a C.R.O. across the capacitor, and adjust the variable resistor to change the shape of the wave produced. Vary the value of C and note the change of frequency and waveform.

The small Unilab coil (9500 + 500 turns) on C-cores may be used in place of this large coil.

Demonstration 9.23. (AF). You can use the apparatus of Demonstration 9.14 to generate audio frequencies. First insert a loudspeaker (5 kilohms) in the H.T. lead and reduce the capacitance to $0.004 \mu\text{F}$. Increase the H.T. supply voltage if necessary.

Hear and see the effect of reducing the capacitance to (say) $0.001 \mu\text{F}$.

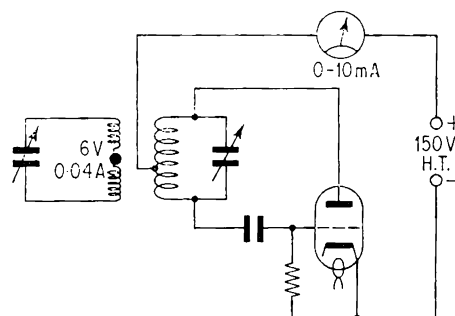


Fig. 400

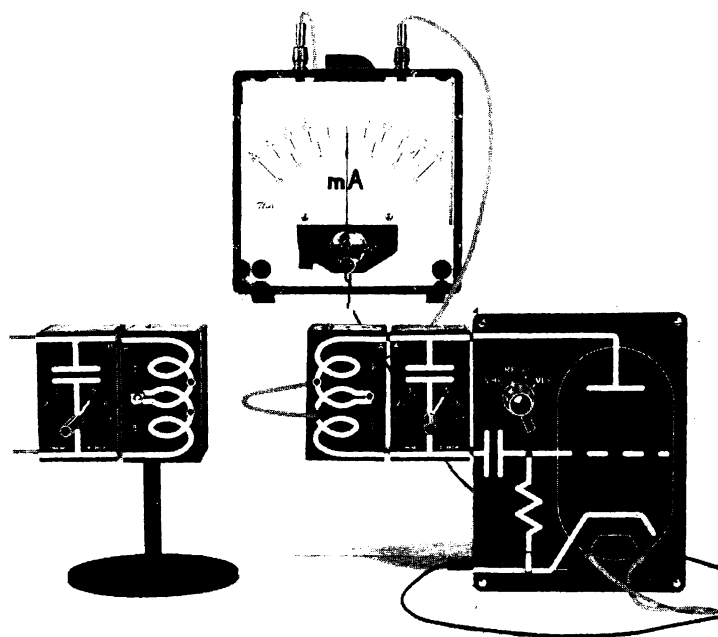


Fig. 401

Demonstration 9.24. (RF). Using the apparatus₁₀ illustrated in Fig. 400 you can generate radio frequencies around 6 MHz. The circuit on the left should be tuned until the bulb glows.

What happens to the anode current when the left hand circuit is tuned to the oscillator frequency, that is, when the bulb glows? Why is this?

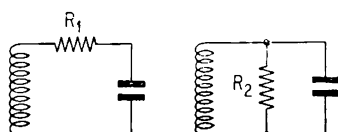


Fig. 402

Fig. 403

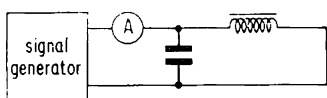


Fig. 404

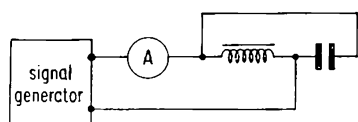


Fig. 405

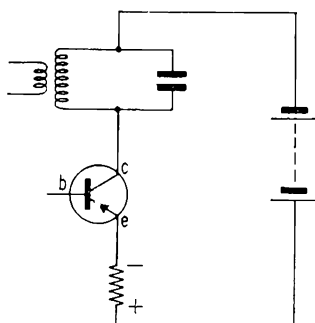


Fig. 406

Problem 23. The damping of a tuned circuit depends on the resistance in the circuit. Should R_1 (Fig. 402) and R_2 (Fig. 403) be large or small to produce the least damping?

Problem 24. Draw a graph showing how the reading on the meter in Fig. 404 would change as the frequency of the constant voltage source was increased. Do the same for the meter readings in Fig. 405.

Problem 25. Complete the circuit shown in Fig. 406 so that it may be used as a transistor oscillator.

(Note: the resistor in the emitter circuit is to prevent large currents flowing through the transistor. If the emitter current increases, the base becomes more positive with respect to the emitter and tends to reduce it again.)

Reactance

To derive the relationship between reactance, frequency, capacitance and inductance is outside the scope of this course, but the results are worth noting.

For a capacitor

$$X_C = \frac{1}{2\pi fC}$$

ohms hertz farads

For an inductor

$$X_L = 2\pi fL$$

ohms hertz henries

As we have seen that the currents in a parallel circuit and the voltages in a series circuit are equal at resonance, X_L must be equal to X_C at resonance.

$$2\pi f_0 L = \frac{1}{2\pi f_0 C}$$

$$\therefore f_0^2 = \frac{1}{(2\pi)^2 LC}$$

$$\therefore f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Problem 26. Draw on a sheet of graph paper a straight line to represent the change of inductive reactance with frequency ($X_L \propto f$) and a curve to represent the change of capacitive reactance with

frequency ($X_C \propto \frac{1}{f}$). The red lines in Fig. 407 represent the difference at various frequencies, that is, the resultant reactance at these frequencies. Plot a graph showing how the resultant reactance varies with frequency. Where is the resonant frequency indicated? Does this graph represent the resultant reactance in a series or parallel circuit?

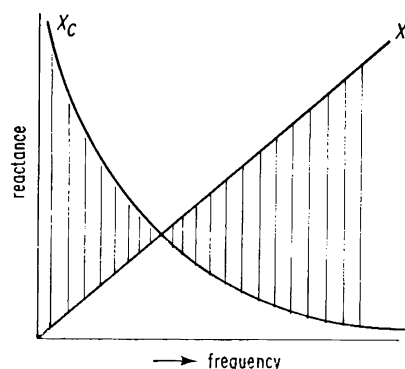


Fig. 407

Project 9.25. Build a model of the graph in Fig. 407 in which the red lines are represented by drinking straws on long vertical wires. Try to arrange the model so that the straws can be slid down the wires until their lower ends lie on the same horizontal line. Their upper ends will then show the required graph.

Summary

Mechanical Oscillations

Normally all oscillations—longitudinal, transverse and torsional—are damped because of internal friction, external friction and radiation.

In a vibration or oscillation energy is continually changing from K.E. to P.E. to K.E. to P.E., etc.

To maintain oscillations, energy is fed into a system at its natural frequency (f_0) or at $\left(\frac{f_0}{n}\right)$ where n is an integer.

Standing Waves

Standing waves are produced by the interference of incident and reflected travelling waves. Such waves often radiate other travelling waves (for example, a vibrating air column or wire radiates sound waves).

Electrical Oscillations

A capacitor stores electrical energy (P.E.). If the capacitor is discharged through a coil, the energy appears in the magnetic field through the coil while charge is flowing (K.E.). When the field collapses the capacitor is again charged up in the opposite direction (P.E.).

A parallel (rejector) circuit has maximum impedance at f_0 . It is a current amplifying device.

A series (acceptor) circuit has minimum impedance at f_0 . It is a voltage amplifying device.

The resonant frequency of a tuned circuit *increases* as C or L are *reduced*.

Optional Extras

Simple Harmonic Motion

In S.H.M. the force acting on a particle is proportional to the displacement of the particle from the origin. It is always directed towards the origin. The displacement of a particle moving in S.H.M. may be represented by a sine curve.

Visual Aids

16 mm Films: Electrical Oscillations and the Electromagnetic Spectrum₃₇ (for teachers).

Space Travel

CHAPTER 10

James Clerk Maxwell

Today we take for granted that waves travel through space. We no longer wonder at radio and television, radar and radio-stars. We have learned to live with electromagnetic radiation of all kinds, VHF, UHF, microwaves, infrared, ultraviolet, X-rays, and gamma rays.

A hundred years ago this amazing spectrum of waves was unknown, and it took the mathematical genius of James Clerk Maxwell to bring it to light. Maxwell was born in Edinburgh in 1831, and from the age of 10 to 16 attended the Edinburgh Academy. When he was only 14 Maxwell won the Mathematical Medal in the Academy and wrote a paper on 'Oval Curves', which was published in the Proceedings of the Royal Society of Edinburgh. Ironically his nickname at school was 'Daftie'!

After attending Edinburgh and Cambridge Universities, Maxwell, at the age of 24, was elected to the Chair of Physics in the Marischal College, Aberdeen. He later became the first Professor of Experimental Physics at Cambridge and directed the plans for the Cavendish Laboratory.

Maxwell's Equations and Electromagnetic Theory

Oersted had shown that a current in a conductor produced a magnetic field, and Faraday had discovered that a changing magnetic field could produce a current in a conductor, but there was no unified theory of electric and magnetic behaviour. This was provided by Maxwell's equations. They stated, mathematically, that a changing magnetic field (B) always produces an electric field (E), and that a changing electric field always produces a magnetic field.

In addition Maxwell used his equations to predict an entirely new phenomenon—electromagnetic waves. He claimed that oscillating electromagnetic fields were propagated through space in the form of waves which carried energy. Such waves were emitted by any *accelerating* electric charge. These results are summarised in Fig. 408.

Maxwell's equations also predicted that the speed of propagation of electromagnetic waves was almost exactly equal to the velocity of light as measured by Fizeau. He concluded that light must be a kind of electromagnetic radiation.

Still there was no direct experimental evidence for the existence of electromagnetic waves. No one had been able to produce such waves from electromagnetic equipment. Then in 1888, a few years after Maxwell's death, Heinrich Hertz investigated the properties

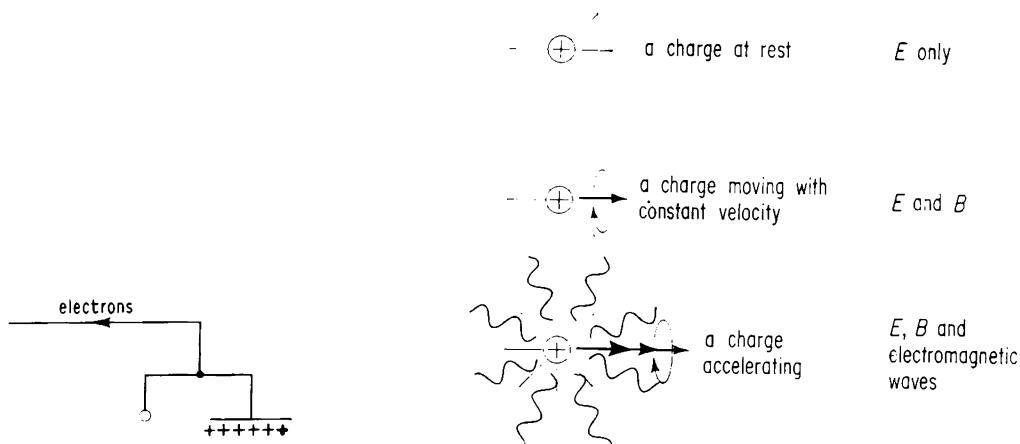


Fig. 408

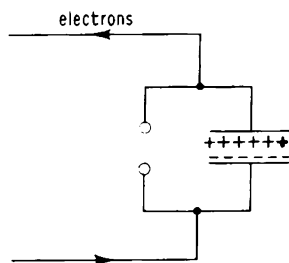


Fig. 410

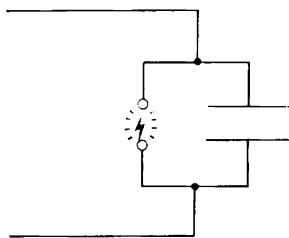


Fig. 411

of electric oscillations in a circuit connected to an induction coil. The circuit consisted of two metal plates and two spheres (Fig. 409). Imagine it as a spark gap in parallel with a capacitor (Fig. 410) in which the plates have been opened up. Each pulse from the induction coil charged up the capacitor until the insulation between the spheres broke down (Fig. 411). The capacitor was then discharged through the ionised air. In this way a damped oscillatory current of about 50 MHz was produced. If Maxwell's predictions were correct, this apparatus should act as a *transmitter* of electromagnetic waves. Hertz used a loop of wire with a small gap in it as his *receiver*. When he placed it several metres from the transmitter, he discovered that a small spark jumped across the gap in the ring whenever the induction coil was switched on.

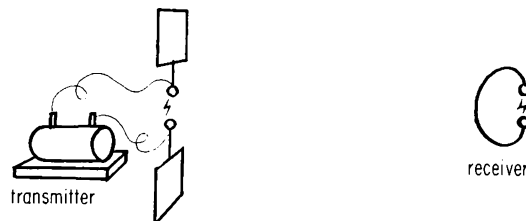


Fig. 409

Hertz showed that these 'rays of electric force', or *radio waves* as he later named them, could be reflected by metal plates and refracted by a giant prism made from half a ton of asphalt. He thus confirmed Maxwell's prediction of electromagnetic waves and showed that they behave like light waves.

Spark transmitters are now illegal, as they radiate energy over a wide band of frequencies and interfere with radio and TV reception, as do unsuppressed sparking plugs in car engines. Thermionic valves and transistors are now used in electronic oscillators, which

are capable of maintaining a constant frequency. The two plates in Hertz's transmitter have now become the aerial, and a similar aerial is used for the receiver (Fig. 412).

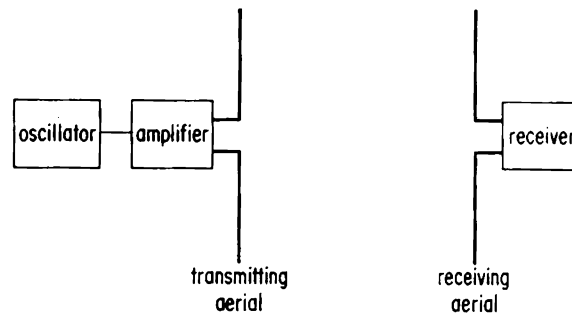


Fig. 412

Electromagnetic Radiation

Electromagnetic waves can best be described by Maxwell's equations. These equations are, however, quite meaningless to anyone who does not have a good grasp of advanced mathematics. In case you don't believe that, here they are!

$$(i) \operatorname{div} \mathbf{D} = \rho$$

$$(ii) \operatorname{div} \mathbf{B} = 0$$

$$(iii) \operatorname{curl} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$(iv) \operatorname{curl} \mathbf{H} = \mathbf{i} + \frac{\partial \mathbf{D}}{\partial t}$$

Cheer up! When Michael Faraday was confronted with Maxwell's mathematics he wrote to him as follows: '... There is one thing I would be glad to ask you. When a mathematician engaged in investigating physical actions and results has arrived at his conclusions, may they not be expressed in *common language* as fully, clearly and definitely as in mathematical formulae?' Even though the answer to Faraday's question may be 'no', it is sometimes worth our while to use models which help us to picture a difficult process. Here are two such models.

Imagine a very long rope with one end tied to a tree. If the free end is wagged up and down waves travel out along the rope towards the tree. The waggler moves the rope vertically and the waves are propagated horizontally. Energy is transmitted along the rope as a wave motion. In a transmitting aerial electric charges are oscillating up and down. These in turn produce electromagnetic waves which carry energy from the aerial. The direction of propagation is perpendicular to the movement of the charges in the aerial.

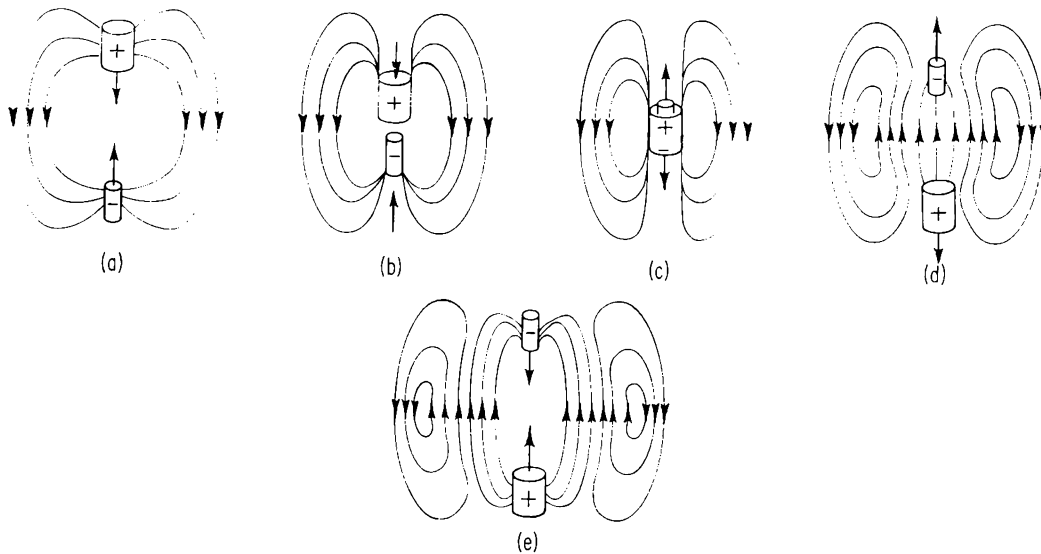


Fig. 413

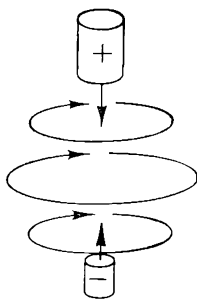


Fig. 414

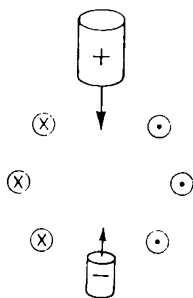


Fig. 415

A more sophisticated model is illustrated in Fig. 413. A positively charged and a negatively charged cylinder oscillate up and down in simple harmonic motion. The negatively charged cylinder can pass through the other. In position (a) the cylinders are furthest apart and starting to move together. At (b) they are closer together and the lines of force still terminate on them. At (c) one cylinder is inside the other so that they produce no electric field. The original field lines do not disappear instantly but form complete loops and move outwards.

At (d) charges are moving apart and field lines of opposite sign emerge. The charges are again furthest apart at (e). As the charges continue to oscillate up and down an expanding pattern of closed loops is formed. These loops are radiated out into space at 3×10^8 m/s.

But this is only half the story. We have not yet mentioned the fact that moving charges produce magnetic fields round them. A positive charge moving downwards and a negative charge moving upwards both produce the same magnetic field around them (Fig. 414). Unlike the electric field, the magnetic field will be in the same direction when the charges are in positions (a)–(d) in Fig. 413, and will change direction only when the charges change direction (Fig. 413 (e)).

The magnetic field lines are perpendicular to the electric field lines, and both are perpendicular to the direction in which the energy is being propagated. To simplify the combined diagram we will indicate magnetic field lines by red crosses and dots as shown in Fig. 415.

Our model bears some resemblance to the state of affairs in a transmitting aerial in which charges run up and down. Fig. 416 shows the pattern produced by such a system. It should, of course,

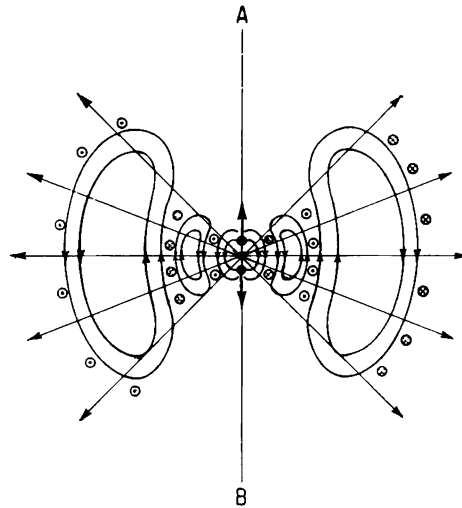


Fig. 416

be a three-dimensional picture, and so you must imagine the diagram rotated about an axis AB to form a laminated doughnut held together by red rings and expanding at the speed of light!

Range of Electromagnetic Waves

In 1901 Marconi succeeded in sending a wireless message across the Atlantic. A ring of high aerial masts in Cornwall was used to transmit the signal, and a kite carried the receiving aerial in Newfoundland. The first trans-Atlantic message was 's' in the Morse Code.

Many scientists thought that the radio waves would shoot straight out into space and could not possibly bend round the curved Earth. In their last assumption they were correct but they had not reckoned on a 'mirror in the sky'. A layer of ionised gas high above the Earth's surface reflects the radio waves so that they can be picked up thousands of miles from the transmitter (Fig. 417).

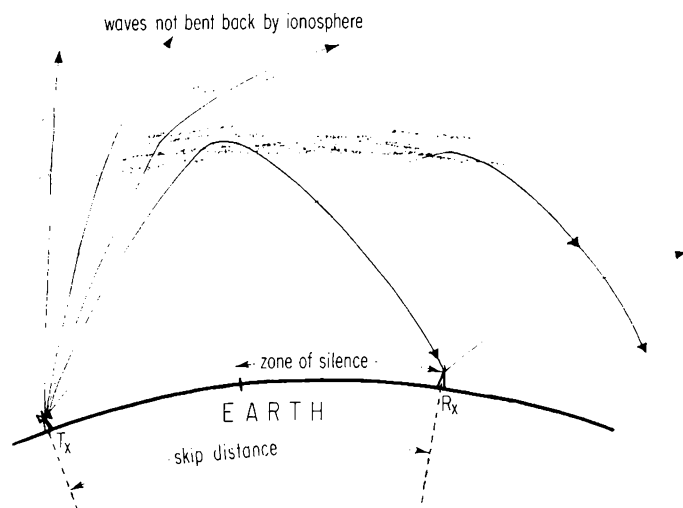


Fig. 417

Marconi's signal bounced backwards and forwards between this ionised layer and the surface of the Earth until it reached Newfoundland.

Only waves striking the ionosphere above a certain angle of incidence will be reflected: others simply pass through the electrified layer. There is therefore a minimum distance between the transmitter and the first reflected signal. If this is further than the range of the direct signal, there is a 'zone of silence' in which reception is impossible. At very high frequencies radio waves are not reflected at all by the ionosphere, and other devices have to be employed for ultra-high frequency transmissions over long distances. Television programmes transmitted from America to Britain are reflected (or re-radiated) from communication satellites such as Telstar or Earlybird.

Electromagnetic waves transmitted from a distant galaxy thousands of millions of years ago carry enough energy to induce currents in the aerial of a giant radio telescope today. Similarly the atomic motions in distant stars emit light which our eyes can detect over millions of millions of miles. Again it was Maxwell who predicted from his equations that the intensity of electromagnetic radiation should fall off much more slowly with distance than the intensity of the electric field round a static charge or the magnetic field round a pole. The latter falls off inversely as the second power of the distance (that is, according to the inverse square law $1/d^2$), but electromagnetic radiation falls off as the first power of the distance ($1/d$). At twice the distance from a source of electromagnetic waves the intensity is halved not quartered.

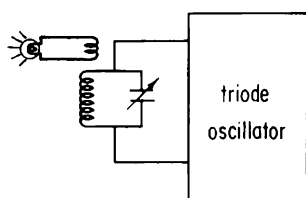


Fig. 418

Transmitters

We have seen that the first radio transmitter was made by Hertz. It was a spark transmitter and radiated energy over a band of frequencies. Spark transmitters were superseded by triode oscillators, in which the frequency could be much more easily controlled by varying the values of capacitance and inductance in the circuit. In the following demonstrations we will use triode valves to produce high frequency oscillations. When the output is then coupled to a suitable aerial system, energy is radiated in the form of electromagnetic waves.

Demonstration 10.1. A simple triode oscillator₁₀ operating at around 6 MHz is suitable. The single loop coil and bulb, shown in red, may be used to indicate the oscillations (Fig. 418).

A second tuned circuit, containing an indicator bulb, may be brought close to the oscillator (Fig. 401, page 146). By varying the capacitor, this circuit can be tuned to the frequency of oscillation as indicated by the maximum brilliance of the bulb.

Demonstration 10.2

(i) The same valve₁₀ may be used to generate very high frequencies (VHF) of the order of 140 MHz. Fig. 419 shows the apparatus in which the inductor is a single loop and the capacitor is the capacitance between the wires in the circuit. If the speed of

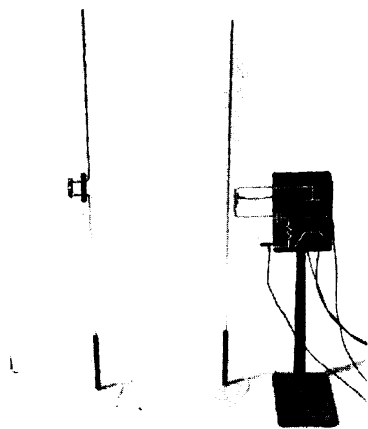


Fig. 419

electromagnetic waves is 3×10^8 m/s, what is the wavelength of this radiation?

A half-wave dipole may be coupled to the oscillator to act as a radiating aerial. A second dipole, fitted with a bulb at the centre will pick up enough energy to light the bulb some distance from the transmitter. What happens to the brightness of the bulb if the aerial is rotated through 90° ? What does this tell you about the radiation?

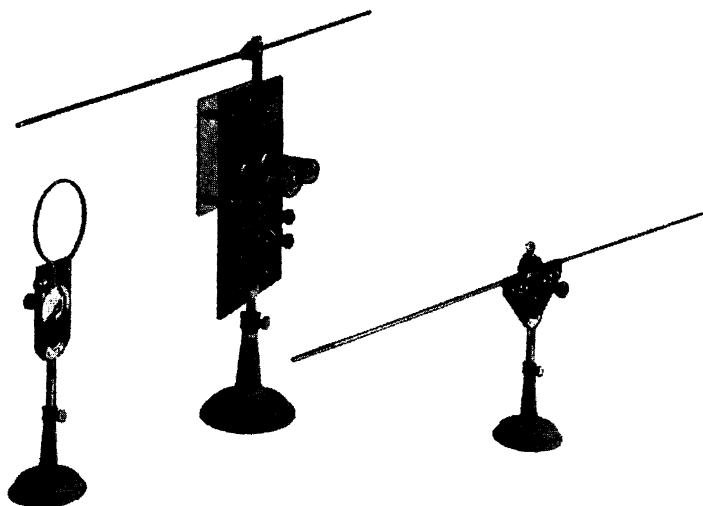


Fig. 420

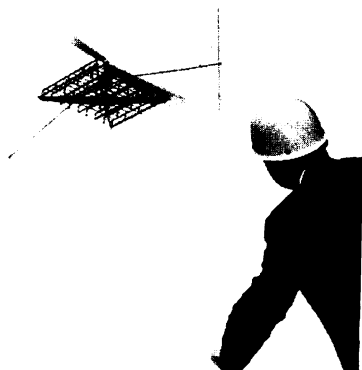


Fig. 421

(ii) An alternative oscillator/transmitter, operating at 150 MHz is shown in Fig. 420. Oscillations may be detected by bringing a neon lamp or fluorescent tube close to the oscillator coil, or by a small bulb in a resonant tuned circuit (loop and capacitor). Electromagnetic radiation from the transmitting aerial can be picked up by a dipole several metres away. This can be indicated by lighting a bulb or operating a galvanometer via a rectifier.

Energy carried by electromagnetic waves has been used to drive a small helicopter (Fig. 421). The wires merely keep the helicopter centred over the radio beam.

Microwaves

The oscillators used in the last demonstration produced waves about 2 metres long (150 MHz). It becomes increasingly difficult to use triodes for frequencies much higher than this, and above 1000 MHz (1 GHz) the physical dimensions of the valve become microscopic. The grid wires are only a few microns in diameter; the grid is less than 10 microns from the cathode and the maximum power output is no more than 1 watt.

About 30 years ago the Varian brothers constructed an entirely new device for producing and amplifying extremely high frequencies—the klystron. We cannot discuss the theory of it

klystron at this stage, and we will have to be content to call it a 'black box'. The term box is in fact quite appropriate, as the klystron does contain a box or *resonator* which supports a trapped electromagnetic wave of one particular frequency—the resonant frequency of the box. The wavelengths of microwaves are of the same order of magnitude as the wavelengths of sound waves in air, and microwave resonators are physically similar in size to acoustic resonators.

The great advantage of the klystron over the triode is that for a given frequency it can be made physically bigger and therefore capable of producing much more power. Operating at thousands of millions of cycles per second it can deliver millions of watts! Klystrons have been used to produce powerful radio signals which, when bounced off Venus and Mars, enabled the distance of each from the Earth to be calculated.

A gallium arsenide microwave generator is illustrated on the eye of a needle in Fig. 422. This amazing device, which is both cheap and reliable, was developed recently at the Royal Radar Establishment in Malvern. It can supply microwaves at frequencies around 10^{10} Hz.

In the following demonstration a small klystron is used to generate 3 cm microwaves.

Demonstration 10.3. Microwave equipment₁₀ can be used to demonstrate the wave-nature of electromagnetic radiation (cf. Book 2, pages 90f).

(i) Transmission of energy. Why does the meter in Fig. 423 show a reading? Where does the energy come from?

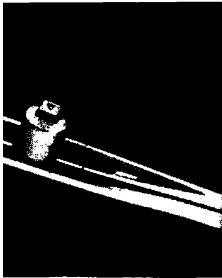


Fig. 422

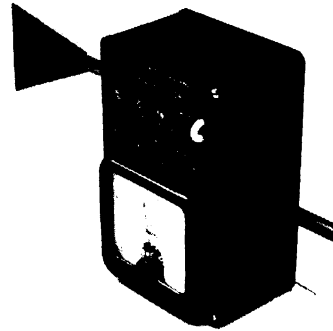


Fig. 423

(ii) Rectilinear Propagation. Move the receiver to different positions and note the meter readings.

(iii) Transmission and Absorption. What materials allow electromagnetic radiation to pass through?

(iv) Reflection. Can the 3 cm waves be reflected by a metal plate? Compare the angles of incidence and reflection.

(v) Refraction. Pass the waves through a prism full of paraffin or a triangular wooden prism. What happens? What can you conclude about the speed of the waves in the prism?

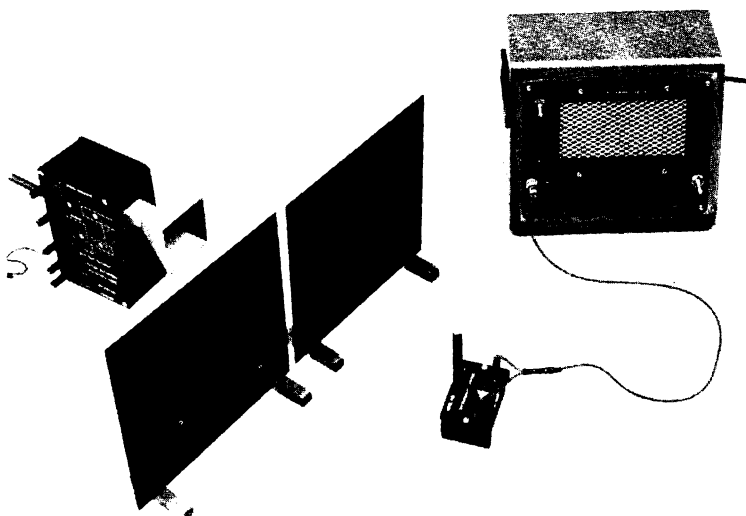


Fig. 424

(vi) Diffraction. Use two metal plates to form a narrow slit in front of the transmitter. Use the diode probe to investigate the strength of the radiation behind the slit. Does the intensity fall off sharply as the probe is moved? Explain the results obtained.

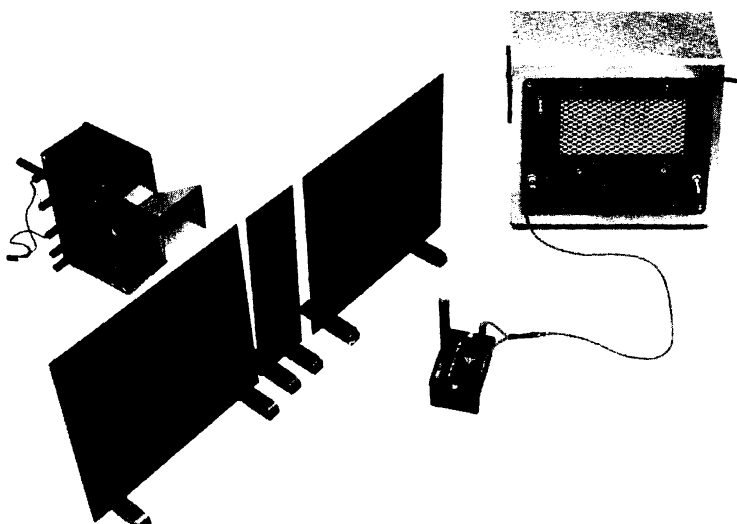


Fig. 425

(vii) Interference. Use the apparatus illustrated in Fig. 425 to investigate the signal strength beyond a double slit. When a minimum position is obtained, cover up one slit and note the effect. Explain it.

Compare the results of this experiment with the ripple tank pattern obtained from two sources. If the separation of the microwave slits and the ripple tank source are the same, the wavelength of the microwaves can be found. Draw the microwave interference lines on a sheet of paper and then project the ripple tank shadow on this paper. Now adjust the frequency of the vibrator until the interference lines coincide, and measure the wavelength of the ripples.

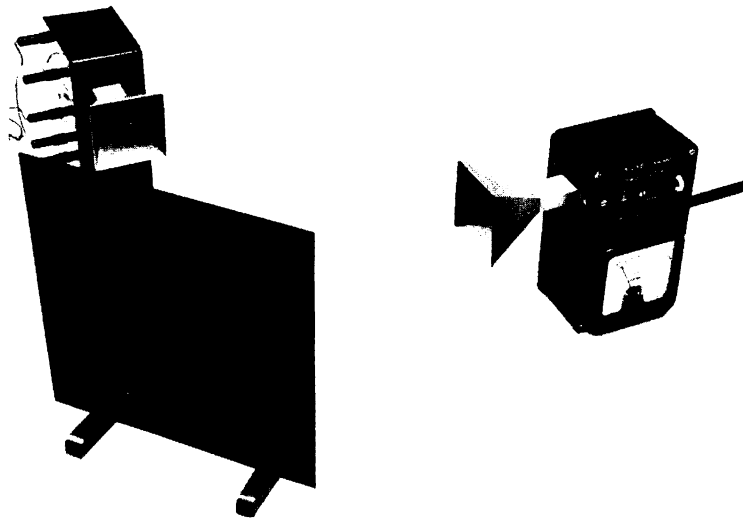


Fig. 426

Fig. 426 shows another way of demonstrating interference. As the reflector is moved, the signal strength at the receiver varies. The waves will sometimes reinforce each other (in phase); at other times they will tend to cancel each other (out of phase). If you imagine the reflector to be the ionosphere you can see why reflected radio signals often 'fade' as the ionised layers move.

Radar

The name was coined from *radio detection and ranging*. Earlier in this course we timed the echo from a wall a known distance away in order to find the speed of sound (Book 2, page 76). If we had known the speed of sound, we could have used this method to find how far we were away from the wall. In radar an electromagnetic wave is reflected from a distant object, and the time taken for the echo to reach the sender is measured electronically. The distance of the object from which the signal is reflected is then calculated.

A narrow beam of microwaves is produced by placing the radiating horn of the transmitter at the focus of a parabolic reflector (Fig. 427). We can use our 3 cm equipment in a similar way.



Fig. 427

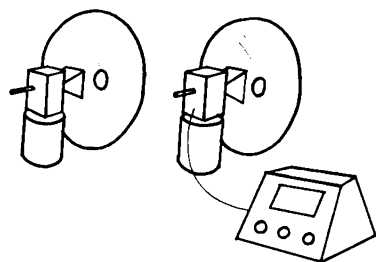


Fig. 428

Demonstration 10.4. Place the transmitter₁₀ horn at the focus of a parabolic metal reflector_{2 4 11} so that a narrow beam of microwaves is produced. The receiver should be placed at the focus of a second reflector, as shown in Fig. 428. Arrange the reflectors so that they point to a region (say) three metres distant. Switch on and note what happens when someone walks across this region three metres from the reflectors. Explain the result.

The last demonstration illustrates the way in which radar signals can be reflected and picked up by a receiver. It tells us nothing, however, about the way in which the time is measured. It would first be necessary to substitute a short *pulse* of electromagnetic radiation for the continuous waves used in our demonstration. We would then have to measure the time interval between sending out the pulse and receiving the echo. Although we cannot do this with our simple microwave equipment, here is a model using sound waves to illustrate the principle used.

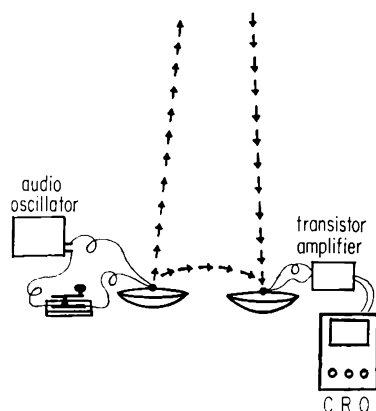


Fig. 429

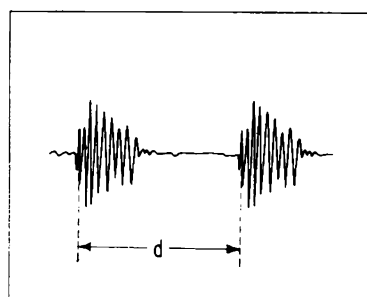


Fig. 430

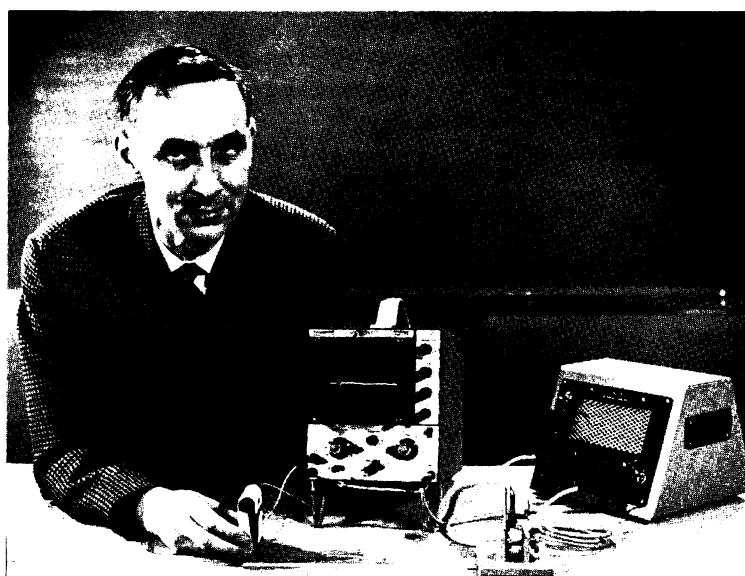


Fig. 431. From the Esso film 'Oscilloscopes and Slow A.C.'

Demonstration 10.5

(i) Place a $2\frac{1}{2}$ in. speaker₁₄ at the focus of a parabolic reflector, and drive it with a 5 kHz signal from an audio oscillator. If a Morse key is included in the circuit, a short burst lasting about 10 milliseconds can be radiated.

A microphone situated at the focus of a second parabolic reflector makes a suitable receiver. The signal should be amplified and passed to a C.R.O. fitted with a long persistence tube. If the S51E oscilloscope is used, set the switched time-base control to 10 ms/cm and the variable control to 'CAL'. Turn the X gain control to its minimum position, and adjust the stability and trigger level controls so that the time-base is triggered by the signal.

With both reflectors pointing upwards as shown in Fig. 429, this apparatus can be used to find the height of the ceiling in your assembly hall.

Tap the key sharply so that a short wave-train is radiated upwards. Some sound will spill over to the microphone (red dotted line) producing a pattern on the C.R.O. There will be a gap before the echo arrives at the microphone to produce a second pattern of waves (Fig. 430). The distance between the leading edges of the two patterns enables us to calculate the time taken for the sound waves to go to and from the ceiling. As the speed of sound is known the height of the ceiling can be calculated.

(ii) Fig. 431 shows an alternative arrangement, in which a pulse from the sweep output of an oscilloscope is fed, via an amplifier, to a small loudspeaker. The signal is then sent out automatically as the time-base starts. The output from the microphone is fed into the C.R.O., and the distance between the start of the time base and the pulse is measured. In the photograph, the apparatus is being used to find the speed of sound by measuring the distance between the loudspeaker and the microphone.

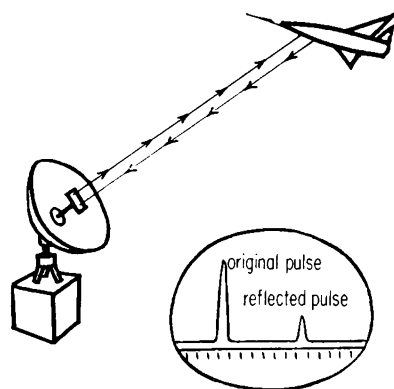


Fig. 432

Problem 1. The apparatus of Demonstration 10.5 is used with the loudspeaker situated 1 metre from the microphone. When the time base is set so that the spot takes 10 milliseconds to move one centimetre, the distance between the leading edges of the two wave patterns is 6 centimetres. Taking the speed of sound as 333 m/s, find the distance from the reflectors to the ceiling.

In radar the same aerial system is normally used to transmit the electromagnetic pulse and to receive the echo. Between pulses the aerial system is switched from the transmitter to the receiver by an ingenious system called a duplexer. Both signals are fed to a C.R.O. which may be calibrated directly in miles or kilometres (Fig. 432).

Radio-astronomy has developed from the use of radar, and the giant radio telescopes are really radar aerials. With them, scientists can measure the distance to the planets or track the course of a meteorite, an artificial earth satellite or an interplanetary spaceship.

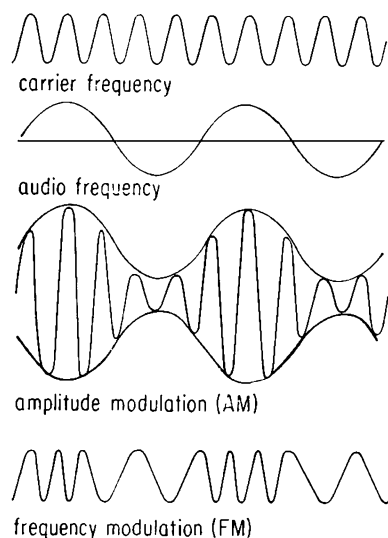


Fig. 433

Communication

As soon as it was realised that energy could be carried by radio waves, attempts were made to use them to transmit information. By the use of long and short bursts of radiation, messages were sent by Morse Code. As radio frequencies are all much higher than the highest audio frequency, we cannot use a radio signal to operate a loudspeaker or earphone. How then can we hear such a signal?

Modulation

One method of carrying information on radio waves is to alter the transmitted signal (carrier wave) in some way which depends on the information being carried (Fig. 433). For example, if we want to send audio frequencies (A.F.), the size of the carrier wave can be altered at the audio frequency. This is called *amplitude modulation* (A.M.). In another method the frequency of the carrier is varied at the audio frequency. This is called *frequency modulation* (F.M.), and is used in the BBC VHF transmitters. We will consider only amplitude modulation in this course.

Demonstration 10.6. A low frequency voltage from a power unit_{N104} or an audio oscillator may be modulated with the slow a.c. generator_{N170} used as a rotary potentiometer. The output should be taken from one yellow terminal and the lower end of a 100 ohm variable resistor (Fig. 434).

By rotating the generator manually or with an electric motor the signal fed to the oscilloscope will vary in amplitude. The depth of modulation may be altered by adjusting the 100 ohm resistor.

Amplitude Modulated transmitter

In a triode oscillator, the amplitude of the oscillations depends on the H.T. voltage. If this is varied at an audio frequency, the amplitude of oscillations varies at the audio frequency. This is

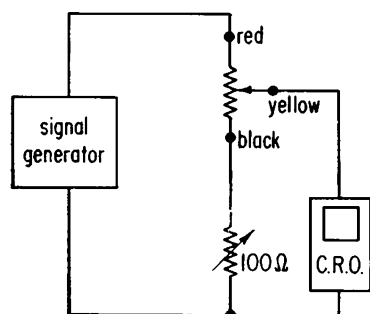


Fig. 434

called *anode modulation*. In the following experiments, high frequency transmitters radiate signals which are amplitude modulated at speech frequencies.

Demonstration 10.7

(i) By the use of the apparatus₁₀ shown in Fig. 435 the VHF oscillator may be anode modulated. A 3W audio amplifier with a low impedance output is adequate. The H.T. supply to the oscillator is fed via the low impedance secondary of the output transformer. A small diode in the middle of the receiving aerial is wired in parallel with the input to a transistor amplifier to act as a receiver.

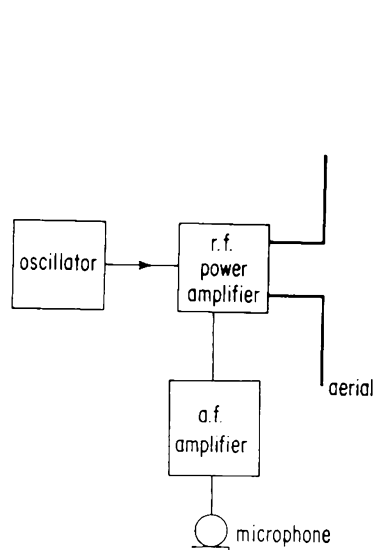


Fig. 436

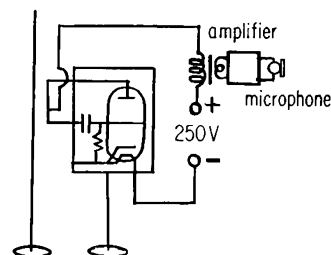
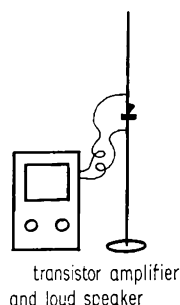


Fig. 435

(ii) The Russian UHF oscillator illustrated in Fig. 420 may be modulated in a similar way. If a carbon microphone and 6V d.c. supply are used, no audio amplifier is needed.

(iii) The Unilab 3 cm transmitter may also be modulated. A 1 watt A.F. amplifier is adequate, and the audio signal should be fed via $1\ \mu\text{F}$ capacitors to the klystron cathode and reflector. The internal modulation must be switched off.

In practice an oscillator is not normally modulated directly, as this affects the frequency to some extent. The oscillator output is fed to a power amplifier, the output of which is controlled by an audio signal to produce amplitude modulated waves (Fig. 436).

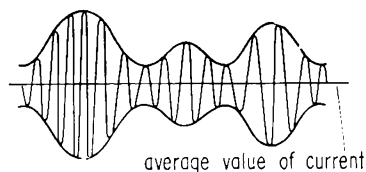


Fig. 437

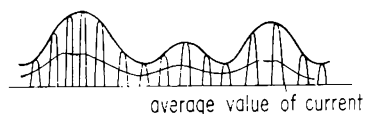


Fig. 438

Demodulation

If an amplitude modulated carrier wave such as is shown in Fig. 437 were picked up by a receiver, amplified and passed through a loudspeaker, nothing would be heard. The average value of the current would be zero, and it would not vary at the audio frequency. To obtain the audio frequency component the signal has to be demodulated or detected. This is most easily accomplished by passing the signal through a rectifier, so that only pulses in one direction remain (Fig. 438). The average value of the current is now changing at the audio frequency and this will be heard in the loudspeaker.

A Simple Receiver

In a radio receiver one particular frequency must normally be selected from a number of different frequencies present in the aerial. To do this the aerial and earth are connected to a tuned circuit (Fig. 439). The variable capacitor is then adjusted until the resonant frequency of the circuit is the same as the frequency of the signal required. As the tuned circuit will then have its maximum impedance to the required frequency, a large voltage at that frequency will then be produced across it. Other voltages at unwanted frequencies will normally be much smaller.

If you live fairly close to a BBC transmitter, the following receiver should enable you to receive the programmes.

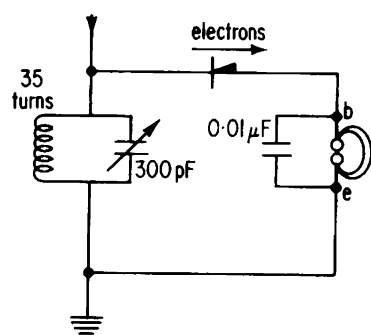


Fig. 439

Experiment 10.8

(a) Wind 35 turns of insulated wire on to a ferrite rod₁₄ and connect the ends to a variable capacitor. Wire the rest of the circuit as shown in Fig. 439. You will need a good high aerial made from at least 20 metres of wire and a good earth (for example, a metal water pipe) to receive a reasonable signal.

The capacitor across the earphone acts as a smoothing capacitor as far as the radio frequency component is concerned. It must not, however, be so large that the audio frequency component is also smoothed out!

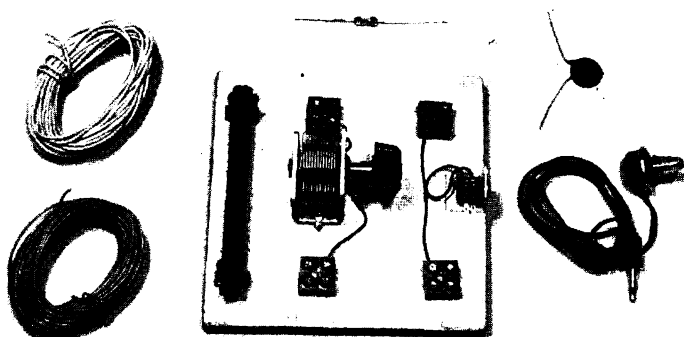


Fig. 440

Fig. 440 shows a simple method of mounting the components so that they can be quickly wired up.

(b) The output from this simple receiver may be improved by adding an amplifying stage (Fig. 441). To do this disconnect the earphone and wire *b* to the base and *e* to the emitter of a transistor. The earphone may then be connected to the collector and the negative terminal of a 1.5 volt cell. The positive terminal should be wired to the emitter.

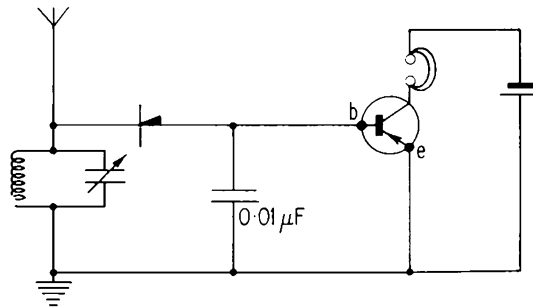


Fig. 441

Project 10.9. Figs. 442 and 443 show the circuit of a simple but very effective two transistor radio.

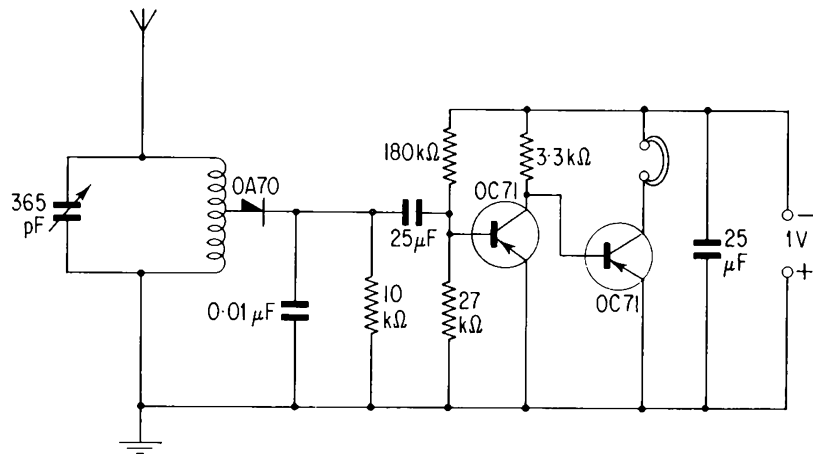


Fig. 442

The Electromagnetic Spectrum

In an earlier part of this course you were introduced to electromagnetic radiation (Book 2, Chapter 6). In this chapter we have looked at the lower electromagnetic frequencies—radio waves—in more detail. Our study of the visual spectrum (Book 2, Chapter 7) will be continued in the next chapter, and gamma rays will be considered in the final chapters of this volume. To complete the picture let us now look briefly at the remaining parts of the electromagnetic spectrum; infrared, ultraviolet and X-rays.

Infrared

In 1800 Sir William Herschel placed a black bulb thermometer in various parts of the sun's spectrum. He discovered that the highest reading was obtained *beyond* the red end of the spectrum. He concluded that the sun was radiating energy at frequencies too low to be detected by the eye, and he called it *infrared radiation*. You have seen various ways of detecting this radiation (Book 2, Chapter 8), which is produced by the thermal motions of molecules. In the following demonstration further evidence is provided of infrared rays.

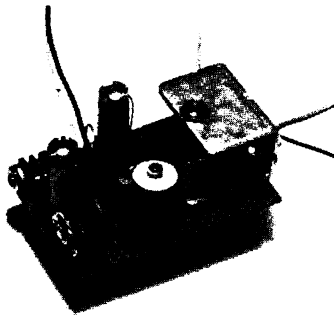


Fig. 443

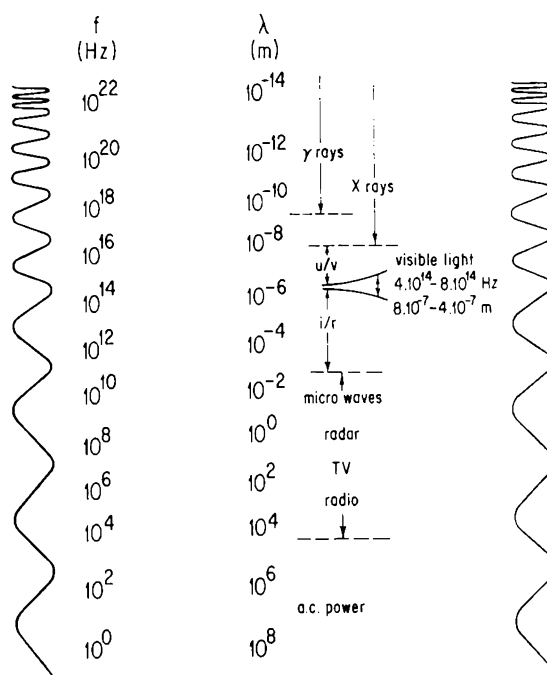


Fig. 444

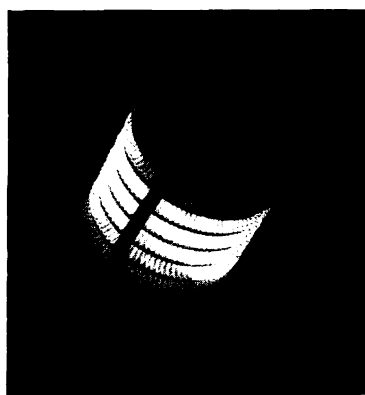


Fig. 445



Fig. 446

Demonstration 10.10. Connect an electric heater to a variable transformer, and adjust the voltage until it is as high as possible without the heating element glowing. Now photograph the element in a totally dark room, using infrared film. The photograph in Fig. 445 was taken with Polaroid type 413 film using an aperture of f22 and a close up lens. The exposure was 80 seconds.

Infrared photography is used for many military purposes. In night reconnaissance flights concealed installations can be photographed by the heat radiation they give off, although they would be quite invisible by day. Fig. 446 shows one of the many industrial applications of infrared radiation. The paintwork of a car is being rapidly dried.

Vibrating molecules will absorb infrared radiation if their natural frequency corresponds to the frequency of the radiation. Chemists investigate molecular structure by observing the frequencies at which infrared rays are absorbed.

Ultraviolet

About a year after Herschel discovered infrared rays, the German scientist Johann Wilhelm Ritter found that invisible rays beyond the violet end of the visible spectrum produced various chemical changes. Photographic plates were later found to be affected by this *ultraviolet radiation*.

Ultraviolet rays are very important for health—they produce Vitamin D in our skins but an overdose can be harmful. Fortunately the Earth's atmosphere absorbs most of the harmful rays. On a high mountain the intensity of ultraviolet radiation from the sun is much greater, and it can produce severe sunburn. Suntan

lotion and the pigmentation on the skin of the dark-skinned races act as ultraviolet filters protecting the body cells from the harmful rays. In green plants ultraviolet radiation produces photosynthesis.

When ultraviolet rays strike a clean metal surface they can knock out electrons (see Demonstration 6.1, page 78). They will also cause various substances to glow (fluoresce).

When an atom in the fluorescent material absorbs energy at a high frequency (ultraviolet), one of its electrons is raised to a higher energy level (Fig. 447). The atom returns to its original state in more than one step, and in so doing radiates energy at lower frequencies (light).

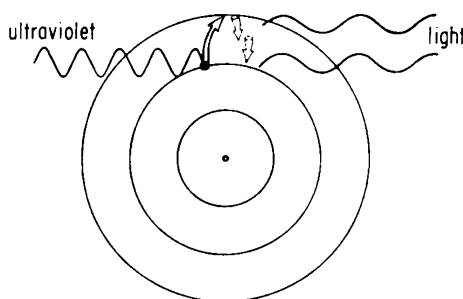


Fig. 447

Teeth, finger nails, fluorescent paints, phosphors and clothes washed with modern detergents are examples of materials which fluoresce in this way. Egg shells also fluoresce. You can check that your grocer has sold you fresh eggs by examining them in ultraviolet light. If they are fresh, their shells should glow a reddish colour. If they produce a purple glow . . . beware!

A mercury vapour lamp is rich in ultraviolet radiation, and provides a useful source. As glass is practically opaque to this radiation, mercury vapour lamps normally have a quartz bulb or at least a quartz window. Fluorescent tubes also contain mercury vapour. The inner surface of the tube is coated with fluorescent powders which re-radiate light in the visible spectrum when bombarded with ultraviolet radiation.

Project 10.11. Devise an experiment to find out to what extent a photographic film is sensitive to ultraviolet radiation. Remember that glass is almost opaque to it.

Never look *directly* at an ultraviolet source.

X-rays

In 1895 Wilhelm Konrad Röntgen was experimenting with a high voltage cathode ray tube when he discovered that a nearby screen covered with a barium salt started to glow whenever the tube was operating. Even when the tube was completely covered with black cardboard the screen still glowed. He placed a book, then a piece of wood and finally a sheet of aluminium between the tube and the screen, and it still glowed. When, later, he put his hand between the cathode ray tube and a photographic plate he

produced a shadow photograph of the bones in his hand. Röntgen called this new radiation *X-rays*. News of Röntgen's X-rays spread like wildfire, and within a year over a thousand scientific articles on them were published.

In January 1896 Punch quipped

'Oh, Röntgen, then the news is true
And not a trick if idle rumour,
That bids us each beware of you
And of your grim and graveyard humour'

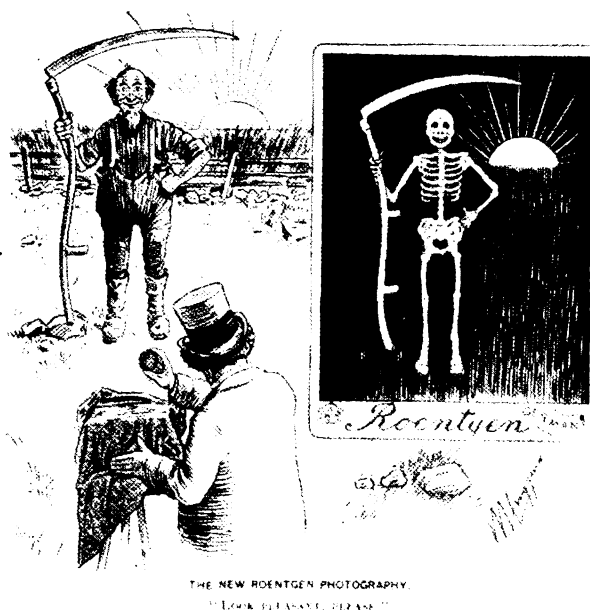


Fig. 448

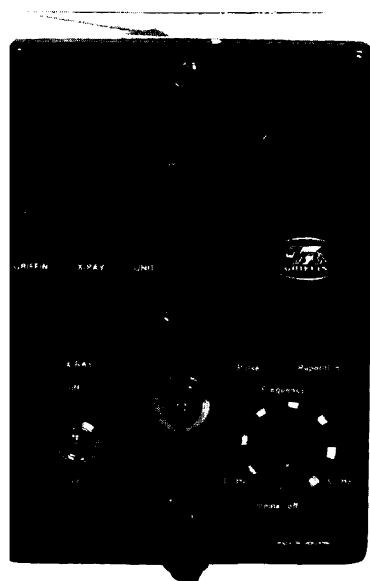


Fig. 449

Demonstration 10.12

(i) Place two identical low capacity electroscopes_{N51/1} side by side, and charge them both to the same positive potential with respect to earth. Bring an X-ray unit₄ (Fig. 449) close to one electroscope and switch it on. Note any change in the time taken for the electroscopes to lose their charges.

Repeat this experiment (a) with the X-ray tube close to the other electroscope and then (b) with the electroscopes charged negatively. What do the results suggest? What was the point of repeating the experiment with the electroscopes charged negatively?

(ii) Connect the neon bulb from the electromagnetic kit_{N92} to a d.c. supply and increase the voltage until it is barely sufficient to cause the bulb to strike. This is about 60V.

Now bring the bulb close to the X-ray tube and explain the results obtained.

(iii) Bring the X-ray tube close to the grid of an ionisation chamber which is connected to a 9V supply and d.c. amplifier₁₀ (Fig. 480, page 185). What effect do the X-rays have? Why?



Fig. 451

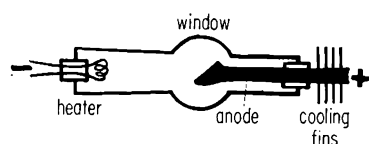


Fig. 452



Fig. 453

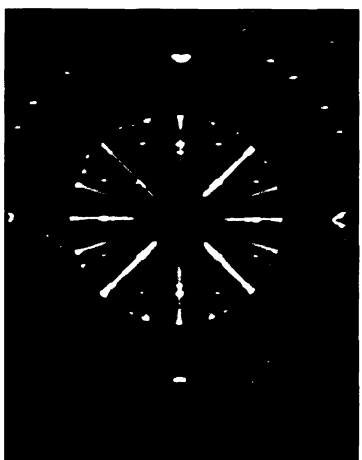


Fig. 454

(iv) Investigate the emission from the X-ray tube using a G-M tube and a scalar or ratemeter.

(v) Bring the X-ray unit close to a continuous cloud chamber N_{28} and note the shower of tiny vapour trails. Can you explain how they are produced?

(vi) Place a metal object on top of a black light-tight envelope containing a sheet of high speed film (Polaroid₂₅ type 57, 3000 A.S.A.), and fix the X-ray unit above it so that the tube is about 2 cm from the film (Fig. 450).

Switch on the X-rays for about one hour and then develop the film. This is done by placing it on a hard flat surface and running a rubber roller over it twice. Press moderately hard in order to burst the pod of developer. After ten seconds a print is available (Fig. 451).

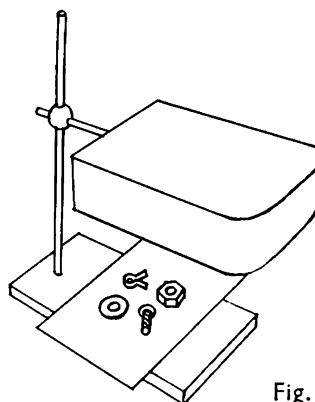


Fig. 450

X-rays are produced when fast electrons are suddenly *decelerated* as they strike a metal target. Fig. 452 shows a modern type of X-ray tube, in which electrons from a heated cathode strike an anode made of a dense metal.

High energy X-rays are produced by high voltages of the order of 200 kV. They have a high frequency and are called hard X-rays. The extent to which they will penetrate a substance depends on its density. The greater the density the less the penetration. Lead is therefore used as a screen. Modern tubes are surrounded by lead except for the window. Hard X-radiation is used to kill cancerous cells, but it can also cause normal cells to become cancerous. Adequate precautions are therefore essential.

Soft X-rays produced by much lower voltages are used for photographic purposes. Fig. 453 shows a dental X-ray photograph taken with such rays.

The passage of X-rays through a gas produces ionisation. The rays knock electrons out of the gas molecules, thus producing positive and negative ions. The gas then becomes an electrical conductor.

The arrangements of atoms in crystals and in the molecules of living bodies have been found in an ingenious way. X-rays are diffracted by the atoms and the pattern produced analysed by computers in order to find the atomic architecture. Methods of this kind were used to determine the positions of the thousands of atoms in the myoglobin molecule. Fig. 454 shows the pattern produced by a tin oxide crystal.

X-ray diffraction is discussed more fully on page 219.

Summary

Electromagnetic radiations include
 radio and TV waves
 microwaves
 infrared radiation
 visible light
 ultraviolet radiation
 X-rays and γ -rays.

Visual Aids

- Charts:* Electromagnetic Waves₃₅.
 Electromagnetic Radiation₄₇.
 Communication by Wire and Wave₄₅.
 Range of Electromagnetic Waves₄₆.
 Principles of Radio. 2. Reception₃₀.
- Filmstrips:* Introduction to Radio₄₃ CGA.B129.
 Radio₄₃ CGA.B259.
 Radio, Radar and Television₃₀ 5153.
 History of Radio₃₅ E.50.
- 8 mm Cassettes:* Microwaves₁₉ (BBC) 526.R37.
 Radar₁₉ (BBC) 526.R38.
- 16 mm Films:* Electromagnetic Waves₃₄ Pt. 1. Discovery and Generation.
 Electromagnetic Waves₃₄ Pt. 2. Properties and Behaviour.
 X-rays₃₁ 2D.1904.
 Principles of X-rays 2D.2230.
 Essential Rays₃₆ 428.106L.
 Pan-Tele-Tron₃₆ 429.106L.
 The Magic Window₃₆ 431.106L.
 From Us to View₃₆ 522.92L.
 Spectrum₃₆ 835.106L.
 Development of Communication₂₉ 20.3866.
 Mirror in the Sky₃₄.
 Calling all Boys₃₆ 1473.106L.
 How does Radio Work₃₆ 1580.106L.
 Impulses₃₆ (NATO).
 The Radio Sky₃₉.
 Girdle round the Earth₃₄.
 The use of Centimetre Waves in Teaching Optics₃₇
 (for teachers).

Spectra—The Give-away Lines

CHAPTER II

In common with other types of electromagnetic radiation, light is produced by electrically charged particles *accelerating*. Electrons, for example, are accelerated to enormous speeds in a synchrotron. As they speed up they radiate energy in the form of light.

In this chapter we will investigate the emission and the absorption of electromagnetic radiation in the visible spectrum. First, however, you may like to revise the work on colour from an earlier part of the course (Book 2, p. 102 f.).

History of Spectroscopy

For thousands of years man watched and wondered about Nature's giant spectrum, the rainbow (cf. Genesis 9.13). Then in 1666 Newton discovered that when a shaft of sunlight passed through a prism it produced the same range of colours—red, orange, yellow, green, blue, violet. Newton called this the *spectrum* and spoke of 'the most surprising and wonderful composition . . . of whiteness'.

Little if any use seems to have been made of Newton's discovery during the next century, and it was not until 1752 that Thomas Melvill published, in Edinburgh, the first description of an *emission spectrum*. He used a prism to study a sodium flame.

In 1802 Thomas Young passed a beam of white light through two fine slits and used his interference theory to calculate the wavelength of the colours in Newton's spectrum. Later, Joseph Fraunhofer increased the number of slits to produce the first *diffraction grating*. This device has largely replaced the prism in modern spectroscopy.

Fraunhofer built a refined form of spectrometer to study the sun's spectrum, and discovered that it was crossed with 'an almost countless number of strong and weak vertical lines'. He found that planetary spectra were similar but stellar spectra differed from that of the sun.

During the first half of the 19th century flame and arc spectra were studied by many scientists, but it was not until 1859 that a general pattern emerged. This was largely due to the work of the German physicist Gustav Robert Kirchhoff. He pointed out that each element *emits* its own unique set of colours (line spectra). He also showed that the element in its gaseous state will *absorb* these same colours of light from white light (absorption spectra).

By stating this general law relating emission and absorption spectra, Kirchhoff was able to explain the dark lines which Fraunhofer discovered across the sun's spectrum. The Fraunhofer lines indicated the presence of elements in the sun's atmosphere. They

included many elements already known, such as sodium and calcium, but one set of lines could not be accounted for. Apparently there was an unknown element in the sun's atmosphere. It was labelled *helium*, after the Greek word for the sun—*helios*. The chemists had already predicted the possible existence of such an element, but another quarter of a century elapsed before Sir William Ramsay first identified traces of helium in the Earth's atmosphere. Later, small amounts of helium were also found in natural gas from the gas wells of Texas.

The work of Kirchhoff and of Bunsen laid the foundations of modern spectroscopy. In the course of their studies they discovered two new alkali metals, caesium and rubidium.

The wavelengths of spectral lines may now be determined so accurately by spectroscopic methods that the international standard of length is now based on the wavelength of the red line in the spectrum of krypton 86.

Schism by Prism

The process of splitting up light into coloured beams is called *dispersion*. The amount by which a beam of light is bent when it enters a block of glass depends on the colour of the light. By using a triangular prism the emergent rays at the violet (short wave) end of the spectrum are bent more than those at the red (long wave) end. This produces dispersion.

Here are a few ways in which a glass prism may be used.

1. Hold a glass prism close to your eye and view a distant line source such as a showcase lamp (Fig. 455).

2. (a) A simple spectrometer can be built from two cardboard tubes supported on Terry clips. The inside of the tubes should be blackened. Glue a piece of black paper or aluminium foil over one end of each tube. Cut a slit in one of the ends and a small hole in the other. Look through the small hole and place the light source beyond the slit (Fig. 456).



Fig. 455

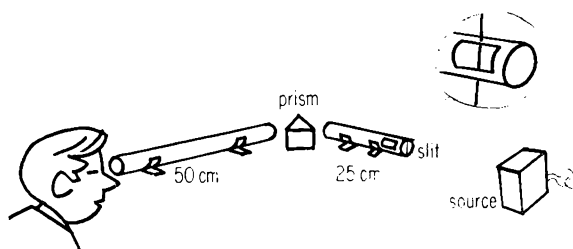


Fig. 456

(b) An alternative arrangement suitable for looking at the sun's spectrum is illustrated in the same diagram in red. Instead of cutting a slit in the end of the right-hand tube, cut a rectangular hole in the side. A fine bright needle is then stuck through the tube as shown. If a beam of sunlight shines on the needle the spectrum can be examined. A black cloth covering the prism and open ends of the tubes will help.

3. (a) To obtain a pure spectrum, that is, one in which the colours do not overlap, it is necessary to use a system of lenses to produce images of the slit. Lens L_1 (Fig. 457) brings the light

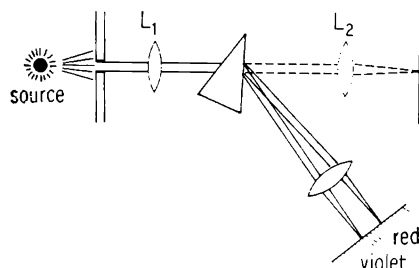


Fig. 457

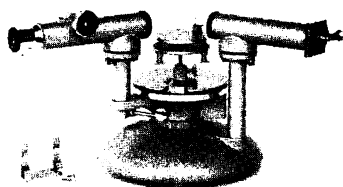


Fig. 458

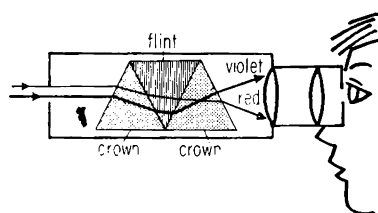


Fig. 459

from the source into a parallel beam and lens L_2 focuses this beam on to a screen so that an image of the slit is formed on the screen. If a prism is introduced into the parallel beam, the light is dispersed and the lens L_2 now produces a series of coloured images of the slit on the screen as shown in the red part of the diagram.

(b) Fig. 458 shows a more sophisticated version of the set-up. The slit and lens L_1 are housed in a tube called the *collimator*, whose purpose is to produce a parallel beam of light. The second lens now becomes a telescope through which the spectrum may be viewed directly. The device is called a spectrometer. It is an important instrument in industry and research.

4. Perhaps the simplest, although not the cheapest, way to study spectra effectively is to use a direct vision spectroscope²⁰. One form consists of a slit, a lens and a three-piece prism made from one flint glass and two crown glass prisms cemented together (Fig. 459). Such spectroscopes are particularly suitable for qualitative studies of emission and absorption spectra.

Grating Spectroscope

Another way of producing a spectrum is by using a diffraction grating. This consists of a piece of transparent material on which a large number of parallel lines are ruled very close together. An explanation of its operation is given in the 'Optional Extras' section on pages 176 f.

To study extended sources such as coloured flames a simple spectroscope can be constructed. It consists of a tube about 30 cm long with a fine slit at one end and a piece of diffraction grating²⁰ at the other. The tube should be black inside to reduce reflections. The spectroscope illustrated in Fig. 460 is made from a length of Dexion Speedframe²² with a roll of black paper inside it.

A good quality diffraction grating is often used now in place of a prism in a spectrometer.

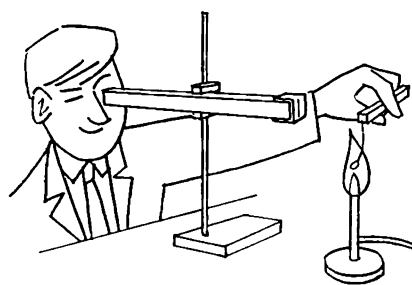


Fig. 460

Studying Spectra

Having discussed various types of spectroscope and spectro-meter we are now in a position to use one or more to study spectra.

Experiment 11.1

(i) Connect a 12V 24W car headlamp bulb to a supply via a 15 ohm variable resistor. Study the spectrum produced at various filament temperatures.

(ii) When the bulb is fully lit, view it through various coloured filters and study the spectra.

(Spectrometers and direct vision spectroscopes are suitable for this experiment.)

Experiment 11.2

(i) Fix a sodium pencil₄ in a bunsen flame and study the spectrum. According to Kirchhoff and Bunsen, less than a ten thousand millionth of a gram of sodium can be detected in a flame! The bright sodium D line has a wavelength of $589\text{ m}\mu$.

(ii) Fix a short length of nichrome or platinum wire in a piece of dowelling and bend the free end of the wire into a small loop. Light a bunsen and adjust it to give a blue flame. Heat the wire loop, dip it into some lithium chloride and then place it on the tip of the inner cone of the flame. Examine the spectrum produced, but don't bring the slit too close to the flame!

Repeat this procedure with other salts, such as calcium chloride, strontium chloride, copper (II) chloride and potassium chloride, using a new wire for each. A piece of asbestos cord soaked in a solution of the salt can be used instead of the wire.

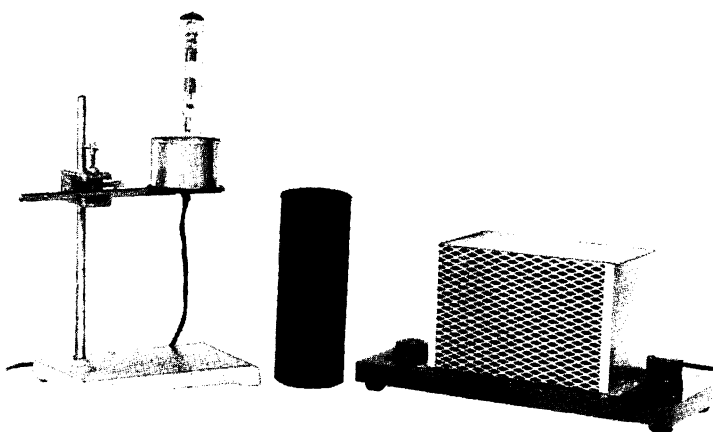


Fig. 461

(iii) Study the spectra produced by vapour lamps₂ containing sodium, mercury or cadmium (Fig. 461), and/or discharge tubes containing hydrogen, oxygen or nitrogen. (Do not look directly at an ultraviolet source.)

(iv) Study the spectra of a neon bulb, fluorescent tube and various street lamps.

(A grating spectroscope or direct vision prism spectroscope is suitable for these experiments.)

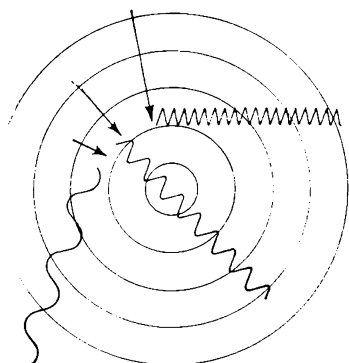


Fig. 462

When a salt is heated in a flame its atoms are excited; that is, some of the electrons are raised to a higher energy level. When they fall back to their original state they emit light (Fig. 462). The wavelength of the light emitted depends on the difference between the energy levels. The line spectra produced in this way help scientists to identify the elements present in the vapour.

Absorption Spectra

Demonstration 11.3

(a) Fix a sodium pencil in a Bunsen flame. Set up a compact light source_{N21} and a large convex lens so that the image of the lamp filament is formed in the sodium flame (Fig. 463). Observe the spectrum with a direct vision spectroscope or a spectrometer.

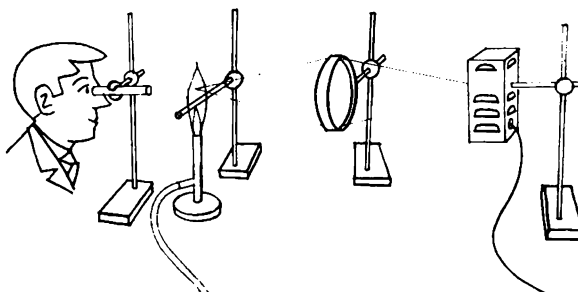


Fig. 463

Describe what you see (i) when the beam is interrupted so that only the sodium flame is being examined and (ii) when the beam is shining through the flame.

(b) You may also like to examine the absorption spectrum of chlorophyll by passing white light through a solution of chlorophyll in alcohol.

Provided you can find a day when the sun will stay out long enough to enable you to set up your apparatus, it is worth while studying the solar spectrum. Remember never to look through any optical instrument *directly* into the sun.

Experiment 11.4

(i) Use the simple spectrometer illustrated in Fig. 456 to study the sun's spectrum. Reflect the sun's rays on to the needle with a large parabolic mirror.

(ii) Alternatively, direct the sun's rays into a very narrow slit on a spectrometer (Fig. 458), again using the parabolic mirror. A flint glass prism or 600 lines/mm grating is necessary to see the Fraunhofer lines.

When studying the absorption spectrum of sodium vapour you will see a dark line appear on the continuous spectrum of the white light source. As this dark line occurs at exactly the same place as the bright line of the emission spectrum, the sodium vapour is apparently absorbing from the white light exactly the same wavelength of light as it emits. The energy absorbed in this way is re-emitted in all directions, so that the amount re-emitted in

the viewing direction is small, and consequently the line looks dark against the other colours.

By studying the absorption spectra of the stars, astronomers have found that some are similar to the spectra of elements on the Earth. Other stars have the same spectral lines, but they are slightly displaced towards the violet end of the spectrum. Others, again, have their lines displaced towards the red end of the spectrum—the so-called ‘red shift’.

When a racing car roars towards you, passes, and then tears away from you, the note of the engine appears to change. In the days of steam trains, the note of the whistle appeared to alter as the train approached, passed and moved from you. As the train moved towards you, the waves were ‘compressed’, their wavelength reduced and their frequency increased. As the train left, the waves were ‘stretched’, their wavelength increased and the frequency reduced. This is called the *Doppler effect*. The red shift in the spectrum of a star is another example of the Doppler effect. The star is moving rapidly away from the Earth so that the frequency of the light emitted by it appears to be reduced; that is, the spectral lines are shifted a little towards the red end of the spectrum.

As the spectra of the sun, stars and planets all contain the same spectral lines as these found in the spectra of elements on the Earth, it looks as though all the known universe may be made of the same kind of stuff. The ‘Big Bang’ theory suggests that it all started with one gigantic explosion.

Optional Extras

Diffraction Grating

The principle of the diffraction grating is illustrated in the following ripple tank experiment, which you should compare with Experiment 4.18 in Book 2.



Fig. 464

Experiment 11.5. Construct a hardboard or aluminium comb with ten teeth 1 cm wide and eleven gaps each $\frac{1}{3}$ cm wide (Fig. 464). Investigate the pattern produced on a ripple tank when plane waves pass through this grating (Fig. 465). Diffraction and interference

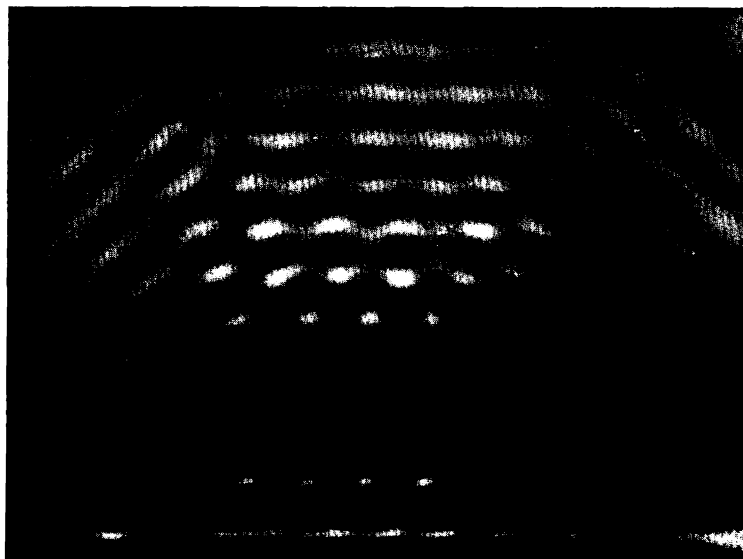


Fig. 465

effects beyond the grating produce first a confused pattern and then plane waves in the original and other directions. What effect has wavelength on the deviation?

The pattern produced by four of the slits in the above experiment is illustrated in Fig. 466. The red arrows indicate the direction of the deviated set of waves. To produce this pattern, the contributions from each slit must be in phase; that is, the difference in

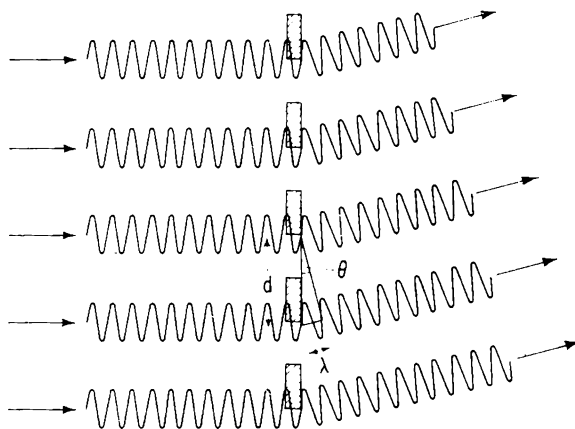


Fig. 466

the path length must be an exact number of wavelengths. In the case illustrated the path difference is one wavelength (λ). From the geometry of Fig. 466 you can see that $\sin \theta = \frac{\lambda}{d}$, where θ is the angle of deviation and d is the distance from one slit to the corresponding point in the next.

The above argument may also be used for light waves. For light of one particular wavelength (λ) there will be a certain direction in which the waves will reinforce each other. This is given by $\sin \theta = \frac{\lambda}{d}$, where d is the distance between adjacent lines of the grating. As $\sin \theta$ is proportional to λ the longer wavelengths deviate more. A diffraction grating used to bend light rays must of course be very much finer than that used in the ripple tank. In fact, the grating space (d) should be of the same order of magnitude as the wavelength of light (λ) if the angle θ is to be measured accurately. A lens system is needed to focus the parallel rays, but the eye itself will act as the necessary lens if the grating is held close to it.

Accurate diffraction gratings are expensive, but replica gratings^{20, 21} suitable for elementary experiments are available cheaply. If you are an enthusiastic photographer you can make a coarse grating yourself.

Project 11.6. Obtain a length of striped shirt material. Black or red narrow stripes on a white background are best. If you photograph a metre of this material containing 500 stripes and the image on the negative is 1 centimetre long, you will have a diffraction grating with 50 lines per millimetre.

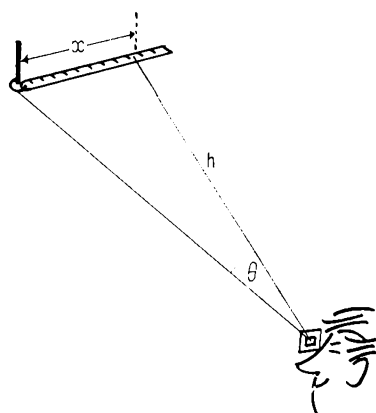


Fig. 467

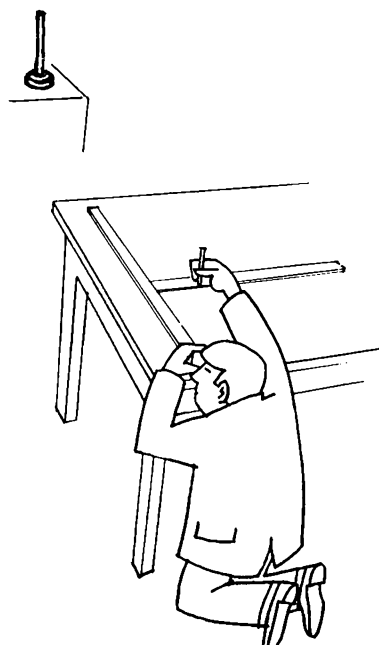


Fig. 468

In the following experiment you can use a diffraction grating to study a spectrum and to measure the wavelengths of different colours of light.

Experiment 11.7

(i) Set up a showcase lamp (60W, clear, tubular) at one end of a darkened room and view it from the other end of the room. Use a diffraction grating held close to your eye to study the spectrum. If different gratings are available, note the difference in the spectra produced by 100 lines/mm, 300 lines/mm, and 600 lines/mm.

(ii) Set up a metre stick at right angles to a line from you to the lamp (Fig. 467). Cover the lamp with a red gelatine filter and view it through a 600 line/mm diffraction grating. Ask your partner to place a pencil against the metre stick in line with the red image. The distance from the pencil to the lamp divided by

the distance from the pencil to your eye is then equal to $\frac{x}{h} = \sin \theta$. If a 600 line/mm grating is used, $d = \frac{1}{6 \times 10^5}$ metres and the wavelength of red light may be found from

$$\lambda = d \sin \theta$$

Repeat this experiment with a blue filter in front of the showcase light and calculate the wavelength of blue light.

(If several pupils are using the same lamp at the same time, each pupil can use two metre sticks, placed at right angles to each other, to find θ (Fig. 468).)

Problem 1. White light is viewed through (a) a prism, (b) a diffraction grating. Discuss what is seen in each case.

Summary

Types of Emission Spectra

1. A **continuous spectrum** is produced by a glowing solid, liquid or gas under high pressure. As the temperature of the source rises, the brightest part of the spectrum shifts towards the high frequency end, that is, from red towards violet. Examining the spectrum of a star will tell us something about its temperature.

2. A **line spectrum** is produced by exciting atoms of a glowing low pressure gas, for example, the atoms of an element vaporised in a flame or excited by a strong electric field.

The atoms of every element produce a different characteristic spectrum. By studying the spectrum produced by a substance a chemist can identify the elements in it. The spectrum has been called the 'fingerprint' or the 'signature' of an element.

3. A **band spectrum** is produced by the vibrating *molecules* in a glowing gas at low pressure. Such spectra can be used to identify compounds.

Absorption Spectra

The glowing vapour of an element emits a bright-line spectrum. If, however, white light shines through it, the atoms of the vapour will absorb the wavelength it normally emits. The bright lines become dark lines against a continuous spectrum.

Rays of Activity

CHAPTER 12

‘I to the Hills . . .’

In the summer of 1894 a young Scottish physicist spent his holiday in the observatory on top of Ben Nevis. He had graduated in Cambridge two years earlier, but whenever possible he made his way back to the Scottish hills. On Ben Nevis he watched the amazing spectacle of his own shadow being cast on a cloud—the *Brocken spectre*. This shadow was surrounded by coloured rings or ‘glories’, which resemble the corona round the sun or the moon. C. T. R. Wilson, for he it was, decided that on his return to Cambridge he would try to make clouds in the laboratory in order to find out the cause of these coloured rings.

You have no doubt noticed that the invisible water vapour present in a warm bathroom will condense on a cold tap or window. The air near the cold object is cooled down so that it can no longer hold all the vapour present. Air may also be cooled by allowing it to expand suddenly. It was this method that Wilson used to produce his clouds. He made a small glass vessel in which air, saturated with water vapour, was allowed to expand by a controlled amount to produce a cloud of tiny water drops. (Cf. Demonstrations 6.8 in Book 1.)

Another Scot, John Aitken, of Falkirk, had shown that condensation would occur only if tiny particles were present to act as *condensation nuclei*. Normally there are enough dust particles in the air to allow water drops to form on them. Wilson discovered, however, that in a super-saturated vapour, that is, one which contains more water than the space can normally hold, drops could still be produced after all the particles had been removed. On what could these drops be forming? Could it be on ‘charged atoms’ or ions?

When Wilson exposed his expansion chamber to Röntgen’s X-rays a fog appeared! The X-rays had produced thousands of ions in the chamber and these had acted as condensation nuclei. The drops formed in the earlier experiment could be explained by assuming that cosmic rays or fragments of radioactive material present in the atmosphere had produced stray ions.

C. T. R. Wilson continued his work on the expansion chamber, and by 1911 was able to show that the track of a fast moving charged particle could be made visible as a white line consisting of tiny drops which had condensed on the ions formed by the particle as it flew through the vapour. The particle itself cannot of course be seen, as is often the case with a high flying aircraft which leaves behind it a clearly visible trail. The Wilson Cloud Chamber has been described as one of the most beautiful devices of modern physics. It revolutionised the study of atomic particles,

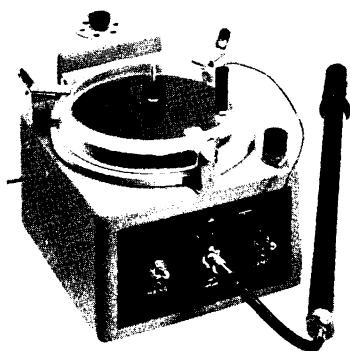


Fig. 469

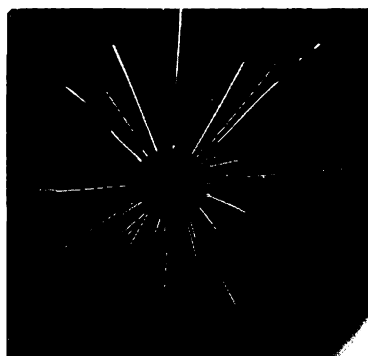


Fig. 470

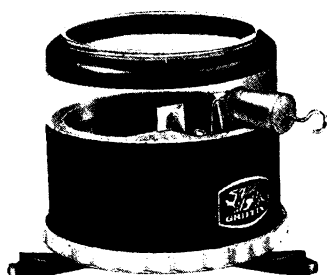


Fig. 471

and led to the discovery of many new particles, all of which are far too small to be seen by the most powerful microscope. For his invention of the cloud chamber Wilson was awarded the Nobel prize in 1927.

Demonstration 12.1

(i) Study the tracks formed when a radioactive source emits radiation in an expansion cloud chamber_{N18} (Fig. 469). Are they (a) straight, (b) produced at regular intervals, (c) equal in length? Do you ever see anything unexpected?

(ii) Repeat the experiment with a ring or semi-circle of paper round the radioactive source. What difference does this make? Particles which can be stopped by paper are called α particles.

A diffusion cloud chamber, capable of producing tracks continuously, was suggested by Langsdorf in 1939. In the model illustrated in Fig. 471, the cooling is produced by solid carbon dioxide below the floor of the chamber. A felt ring in the top of the chamber contains about 1 cm³ of alcohol. The vapour from this alcohol diffuses downwards and is cooled, so that the degree of saturation of the air increases towards the floor of the chamber. After a time conditions are such that the alcohol vapour will condense on the ions formed by the radiations from a radioactive source inside the chamber.

Experiment 12.2

(i) Set up a diffusion cloud chamber_{N28} using about 1 cm³ of methylated spirit and 10 cm³ of 'dry ice'. Make sure that it is properly levelled and that the light source projects a flat beam close to the floor of the chamber (Fig. 472). Adjust the lamp to give the brightest possible tracks. Rub the top of the cloud chamber with a woollen cloth to produce an electric field. This clears the chamber of unwanted ions.



Fig. 472

As in the expansion chamber, the bright white tracks are produced by α particles. What is the average length of the α particle tracks? Are α particles emitted from the source regularly or at irregular intervals?

(ii) Repeat the experiment with a small paper cap over the source, or with a piece of notepaper placed in front of the source. Does any ionising radiation get through the paper? You will have to look very closely to see the fine web-like trails produced by the smaller and lighter β particles which penetrate the paper.

The fine straight tracks are produced by high energy β particles, while lower energy β particles produced small tortuous tracks.

(iii) The chamber is fitted with a very thin aluminium sheet and a thicker sheet. Adjust the source so that it is behind the thin sheet. Do any α particles pass through this sheet? What does this tell you about the atoms in the sheet of aluminium? Are the α tracks beyond the sheet different from these obtained in the original experiment? Why is this?

What do you observe when the source is placed behind the thicker sheet of aluminium? Do β particles pass through both foils?

(iv) Now place a much thicker sheet of aluminium (say 2 mm thick) in the path of the radiation, being careful not to touch the two foils, which are easily damaged. The 2 mm aluminium sheet will stop α and β particles. Are there any tracks formed now? If there are, they will be very short and must be due to a much more penetrating kind of radiation which we call γ rays.

(A 9 μ c radium source held by your teacher outside the chamber and behind a 2 mm sheet of aluminium will allow only γ rays to enter the chamber and produce tiny cloud fragments.

Activity or number of disintegrations per second is measured in *curies*:

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ disintegrations per second}$$

$$1 \mu\text{c} = 1 \text{ microcurie} = 3.7 \times 10^4 \text{ disintegrations per second.})$$

Absorption

The cloud chamber experiments have shown that something is being 'thrown out' of the tiny source. In fact, it looks as though there may be three different kinds of radiation. We have labelled them α particles, β particles and γ rays. You will see later why we have called some of them particles and others rays.

The α particles seem to produce ions easily and lavishly, while the β particles and γ rays do so to a very much smaller extent.

As a rough guide we will assume that, when we are using weak sources,

most of the α particles are stopped by notepaper,

most of the β particles are stopped by 2 mm of aluminium,

most of the γ rays are stopped by 2 cm of lead.

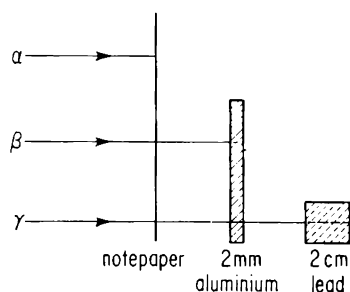


Fig. 473

The Silver Lining

How were these radiations discovered? To answer this we must go back to a dull, cloudy day in Paris during the winter of 1896. Henri Becquerel and his father had specialised in the study of substances containing uranium, and in particular they were interested in the fluorescence (glowing) of uranium salts. When in the previous year Röntgen had produced X-rays in a discharge tube the glass fluoresced, and Becquerel thought that the X-rays might have been produced by this fluorescence. If this were so, might not his uranium salts produce X-rays too?

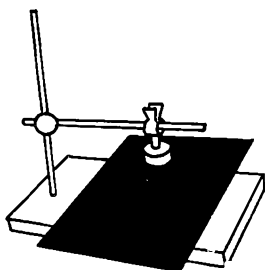


Fig. 474

To test out his hypothesis he wrapped a photographic plate in black paper, placed a silver coin on top and then a crystal of uranium salt on top of that. He exposed the crystal to strong sunlight to make the crystal glow and then developed the film. Success! The photographic plate was blackened except for the part covered by the coin, and so the uranium must have emitted X-rays . . . or something!

Being a careful experimenter he repeated the experiment, or at least he was about to repeat it when the clouds came and covered the sun. He put the photographic plate and crystal into a drawer and waited for a sunny day. Several days passed but the sun refused to shine, and finally, tired of waiting, Becquerel decided to develop the plate without having exposed the crystal to direct sunlight. To his amazement the plate was as black as before! He then prepared and stored the crystals in complete darkness and obtained exactly the same results. Sunlight and therefore fluorescence had nothing to do with the emission of this 'radiation'. Moreover, this radiation, unlike X-rays, was emitted without any excitation. It 'just happened'.

With Becquerel's discovery of this new radiation, *radioactivity* was born, but it was two years later before it was christened by Pierre and Marie Curie.

We can repeat, in modern dress, the famous experiment which led to the discovery of radioactivity.



Fig. 475

Demonstration 12.5. Place a small metal object such as a coin, paper clip, badge or washer on top of a piece of Polaroid photographic film which is wrapped in black paper (type 57, 3000 ASA, 4×5).

Support a $9 \mu\text{C}$ radium source 3 cm above the film (Fig. 474), and leave it for about one hour. Develop the film by placing it on a flat surface and running a rubber roller over it twice, pressing moderately hard.

Is this film being affected by α , β or γ rays? Do they travel in straight lines?

Fig. 475 shows a photograph taken in this way.

Nuclear Expulsion

The discovery of radioactivity established for the first time in history that atoms are not indivisible! A radioactive atom is giving off something; that is, it is breaking up or disintegrating.

We now know from experiment that it is the *nucleus* of the atom that is ejecting particles and rays, and that the *rate* at which a radioactive nucleus disintegrates is entirely independent of any physical or chemical change to which the substance may be subjected.

An atomic nucleus is made of protons and neutrons, which are held together by incredibly strong short range forces. The positively charged protons in the nucleus will, however, tend to repel each other, and, if the nucleus contains more than about 210 nucleons, the short range forces are barely able to counter-balance the long range electrostatic forces of repulsion and so the nucleus is unstable. If, however, part of the nucleus, for example an α particle, is ejected, the nucleus becomes much more stable.

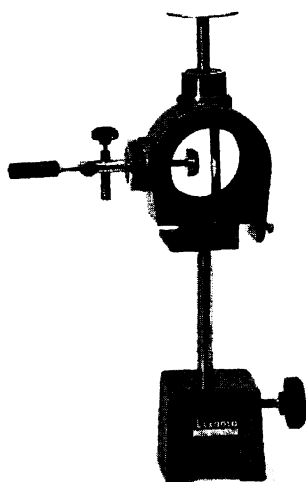


Fig. 476

Ionisation

We cannot see into the nucleus, nor can we see the ejected particles or rays, and so we have to deduce what is happening by observing the effects they produce. You have already seen their ability to affect a photographic plate. Another effect was shown by the cloud chamber tracks.

A high speed particle can 'knock' an electron off an atom, which then becomes a positive ion. The free electron may then attach itself to another atom to produce a negative ion. The water droplets which produce the cloud chamber tracks form on such ions.

Here are some experiments which depend on the ionisation of air.

Demonstration 12.6

- (i) Charge a low capacity electroscope and hold a flame near the plate. What happens? Why?
- (ii) Repeat this experiment using a $9 \mu\text{C}$ radium source instead of the flame.

The electroscope is a *voltmeter*, and in the above experiments it indicates the potential difference between the leaf and the case, which is normally earthed. When the air is ionised, charged particles move between the leaf and the case, thus reducing the charge on the leaf and hence the potential difference between it and the case. Used in this way the electroscope is not a very sensitive instrument, particularly when the leaf is deflected through a large angle.

If a side electrode is connected to the case, the instrument may be used as a *microammeter* (Fig. 476). As such it is a much more sensitive device.

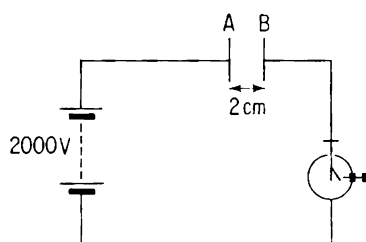


Fig. 477

Demonstration 12.7

- (i) Connect a pulse electroscope as shown in Fig. 477 and place a very high resistance (for example, a handkerchief) between the plates A and B. This allows charge to flow to the leaf of the electroscope so that it is deflected. When the leaf touches the side electrode it is discharged and so falls back. The process is repeated again and again, and the number of pulses per second is a measure

of the *rate* at which charge is flowing between the plates. In other words, the current is proportional to the number of pulses per second.

(ii) Hold a flame or radioactive source between the plates in place of the handkerchief and explain the result obtained.

Fig. 478 shows a pulse electroscopes in use.



Fig. 478. From the Esso film 'Introduction to Radioactivity'

An alternative super-sensitive microammeter, or rather micro-microammeter, is the d.c. amplifier used with a moving coil meter. This is simply a good, well insulated amplifier which enables a small direct current to operate a large demonstration milliammeter (Fig. 479). The reading in the meter is then proportional to the very small current (e.g. 10^{-12} A) through the input circuit of the d.c. amplifier₁₀. As the meter gives a clear direct reading of current, we will use it in future experiments.

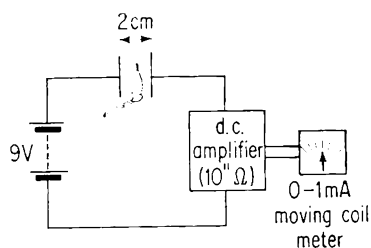


Fig. 479

Demonstration 12.8. Using the circuit illustrated in Fig. 479 read the current produced by (i) a handkerchief, (ii) a lighted match and (iii) a radioactive source between the plates. An input resistance of $10^{11} \Omega$ should be used.

An ionisation chamber₁₀ is illustrated in Fig. 480. It consists of a metal box with a wire gauze lid. A metal plate which is insulated electrically from the box is situated below the gauze. If the box is wired to the positive terminal of a d.c. supply and the plate to the negative terminal, no current will flow. If, however, the air between the gauze and the plate is ionised, current will flow, and this may be measured by inserting a d.c. amplifier, or, alternatively, a pulse electroscopes, in the circuit (Fig. 481).

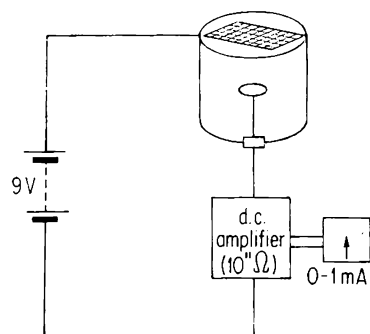


Fig. 481

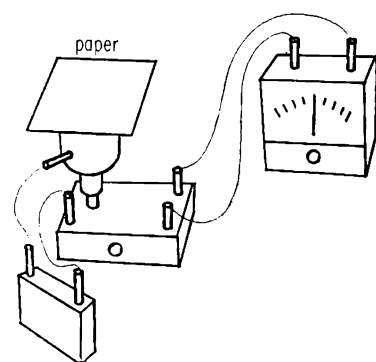
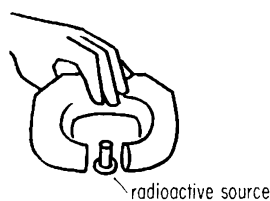


Fig. 482

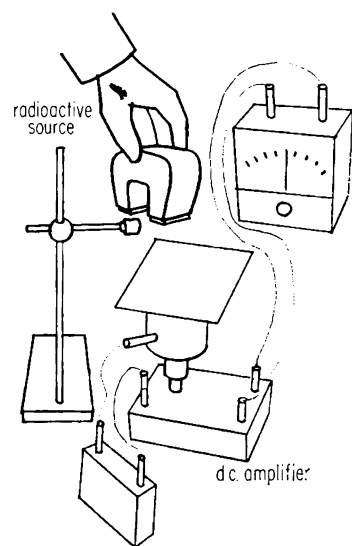


Fig. 483

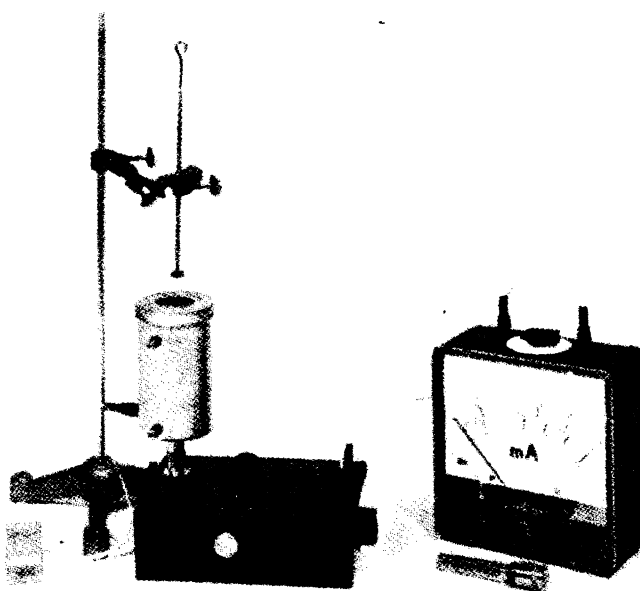


Fig. 480

Demonstration 12.9

(i) Using the apparatus₁₀ shown in Figs. 480 and 481, gradually bring a $9\ \mu\text{C}$ radium source down towards the gauze from a height of about 30 cm. What happens? When the meter reads full scale deflection, insert a sheet of notepaper between the source and the chamber. What difference does this make? What kind of emission causes the big increase in ionisation current when the paper is removed? (A $10^{11}\ \Omega$ input resistor should be used.)

(ii) Find the approximate range of the α particles in air.

(iii) With the meter reading full scale deflection, place a sheet of paper across the ionisation chamber and gradually raise the source. Does the meter still give a reading when the source is raised well above the range of the α particles? Why is this?

Now insert a sheet of aluminium 2 mm thick between the source and the chamber. Does this stop the radiation? What does this tell you?

(iv) With the source about 10 cm above the chamber and a sheet of paper placed over the gauze, hold a powerful horseshoe magnet around the beam (Fig. 482). Is the meter reading affected? What kind of particles are being deflected by the magnetic field?

Demonstration 12.10. Set up the apparatus as shown in Fig. 483 with the $9\ \mu\text{C}$ radium source at the side of the ionisation chamber. Place a sheet of paper over the gauze. Does the meter read when the magnet is not in position?

Now hold the magnet as shown in Fig. 483 and note any change of current. Turn the magnet round so that the poles are reversed and again note any change. Can you deduce the charge on the β particles from the direction in which they are deflected in the magnetic field?

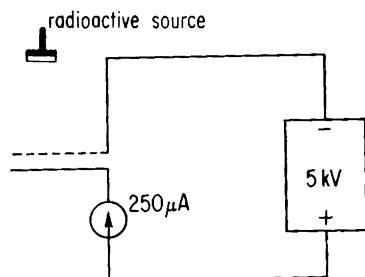


Fig. 484

The Spark Counter

In the spark counter a very high voltage is applied between a piece of gauze and a fine wire stretched just below it. If charged particles ionise the air between the gauze and the wire, sparks are produced. The number of sparks indicates the number of charged particles present in the spark counter.

Demonstration 12.11. Connect a spark counter_{N17} to an E.H.T. supply_{N14} (Fig. 485), and adjust the voltage of the supply until it is just below the point where sparking occurs. Now hold a $9\ \mu\text{C}$ radium source over the counter and gradually bring it down towards the gauze. What happens? Are the particles arriving at regular intervals of time?

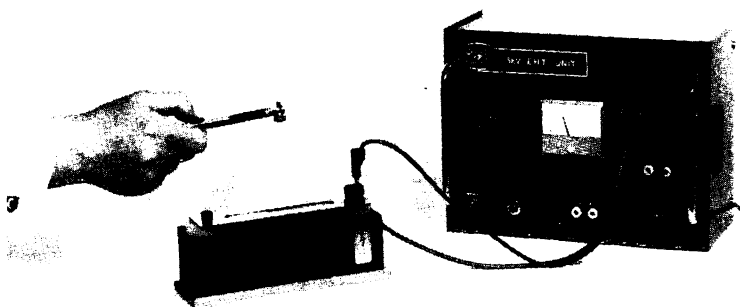


Fig. 485

Place a sheet of paper between the source and the counter. Are the sparks caused by α or β particles or by γ rays?

Can you use this apparatus to find the maximum range of α particles in air?

The ionisation current may be indicated on a microammeter in the circuit (Fig. 484).

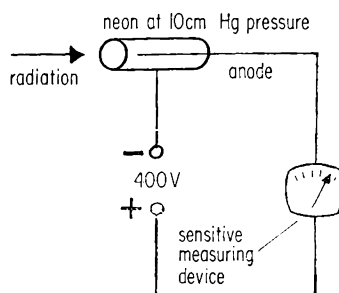


Fig. 486

The Geiger-Müller Tube

In 1928 a very sensitive ionisation detector was invented. It is a modified form of ionisation chamber and spark counter contained in a tube filled with an inert gas, such as argon or neon at low pressure (for example, about 10 cm Hg). Inside the tube there are two electrodes, a metal cylinder which is the cathode and a wire running along its axis to form the anode (Fig. 486). Particles can enter the tube through a mica window at one end. If the tube is to be used to detect α particles, this window must be very thin.

If a particle or pulse of ionising radiation enters the tube, some of the neon atoms will be ionised. The ions formed will accelerate towards the electrodes and cause further ionisation by collision. In this way a single ion can quickly produce many thousands more, and a pulse is indicated on the meter. To prevent this avalanche

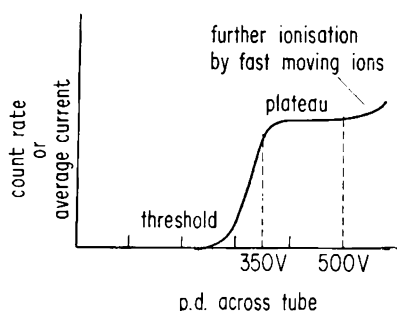


Fig. 487

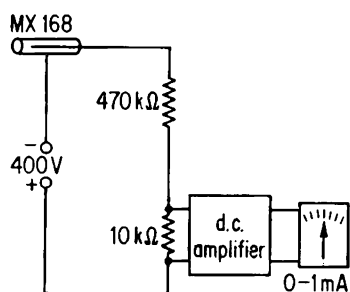


Fig. 488

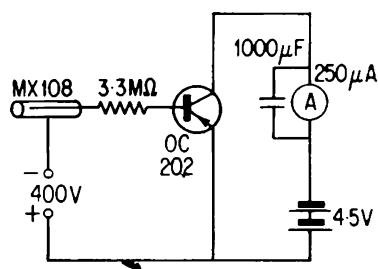


Fig. 489

process reaching the stage where an actual spark takes place, and to clear the tube ready for the next pulse, a quenching agent, such as a trace of bromine gas, is introduced into the tube. In the way we use the tube the size of the pulse produced is found to be the same regardless of the energy or charge of the original ionising particle.

The number of pulses per second or, in the case of the circuit in Fig. 486, the average value of current produced depends to some extent on the voltage applied. The characteristics of one type of Geiger-Müller tube are shown in Fig. 487.

From this graph you can see that if we use a voltage of approximately 400 volts on such a tube, the count rate will not vary when the voltage alters slightly one way or the other. For this reason we normally operate such tubes at a voltage near the middle of the plateau region.

Demonstration 12.12

(a) Connect a Geiger tube (for example, a Mullard MX 168) in the circuit shown in Fig. 488. A d.c. amplifier₁₀ (without input resistor) drives a moving coil meter. This is a primitive form of ratemeter. Notice how the average current varies when a radioactive source is brought close to the tube.

Now fix the source at a point near the tube and investigate the effect of altering the applied voltage.

(b) An alternative circuit using a single transistor is shown in Fig. 489.

Ratemeters and Scalers

In practice there are two different pieces of apparatus which can be used with a Geiger tube. The first is a refined form of the apparatus used in the last experiment. It is the *ratemeter* (Fig. 490). It will indicate the value of the ionisation current averaged

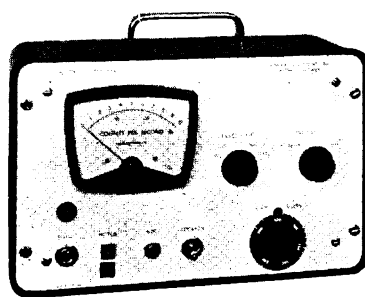


Fig. 490

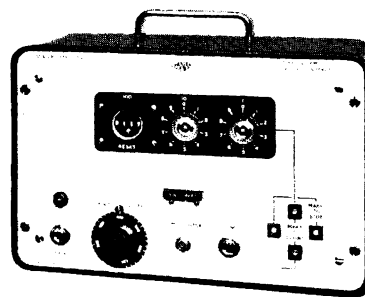


Fig. 491

over a particular time interval which may be selected by a control on the front. The meter dial is normally calibrated in 'counts per second'. In some ratemeters a loudspeaker is fitted so that an audible indication of current pulses is also available.

The Geiger tube may also be used with a scaler (Fig. 491). This instrument counts the pulses and indicates the total on a

series of dials. For quantitative work in radioactivity this is the more useful instrument. The count rate can be determined accurately by timing the number of pulses over a given period of time.

Background Radiation

If a scaler is connected to a G-M tube, occasional pulses will be indicated even if no radioactive source is near. These pulses are produced by cosmic rays coming from outer space, from tiny radioactive fragments present in the atmosphere and, in Aberdeen, from radioactive granite! Allowance must be made for this *background radiation* when using a G-M counter to measure the radiation from a particular source. *How would you do this?* (1)

Demonstration 12.13

(i) Use a Geiger tube with a thin window (for example, Mullard MX 168/01) and a ratemeter or scaler to observe the effects of placing the following materials between a $9\ \mu\text{C}$ radium source and the tube.

- (a) A sheet of thick paper.
- (b) A sheet of aluminium 2 mm thick.
- (c) A block of lead 2 cm thick.

Note the results in each case and explain why they differ.

(ii) Repeat this experiment with

- an α source (for example, Americium-241),
- a β source (for example, Strontium-90),
- and a γ source (for example, Cobalt-60).

(If the thick-windowed version of this tube is used, MX 168, α particles will not be readily detected.)

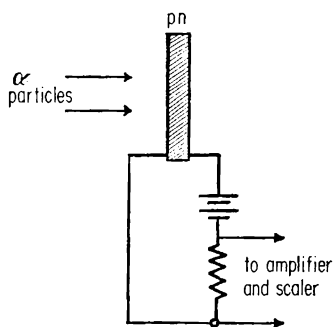


Fig. 492

Solid-state Detector

The last type of radiation detector we will use in this course is the semi-conductor junction or solid-state detector (Fig. 492). One such junction is formed by evaporating a thin layer of gold (about 1 micron) on to a slab of n -type silicon (about 1 millimetre). When an alpha particle enters the detector, electron-hole pairs are produced. These, in turn, cause a current pulse which produces a voltage pulse proportional to the energy of the particle. The voltage pulse is amplified and fed to a scaler or ratemeter.

More elaborate and expensive solid-state devices have been developed to detect other types of radiation.

Demonstration 12.14

(i) Test a solid-state detector₂₃, using a $9\ \mu\text{C}$ radium source and paper, aluminium and lead absorbers. What kind of radiation does *this* device detect?

What is the maximum range of these particles in air at atmospheric pressure?

(ii) Insert the source in one end of a polythene tube about 50 cm long and insert the detector in the other end. When the tube is straight can α particles be detected?

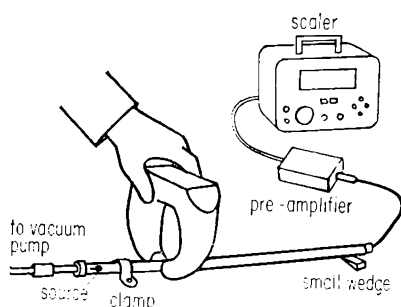


Fig. 493

'Evacuate' the tube and see if the α particles will travel 50 cm in the low pressure air left. Can you explain the result in terms of collisions?

(iii) As the *range* is so much greater in an evacuated tube, any slight bending of the beam of particles can be detected more easily.

Now bend the tube very slightly so that the count rate is very low. Place a powerful horseshoe magnet over the tube as shown in Fig. 493 and note any change in count rate.

Reverse the magnet and again note the rate. What do these results tell you about the particles? From the direction of the magnetic field deduce the charge on the α particles.

Fig. 494 shows some cloud chamber tracks of alpha particles which have been deflected by an intense magnetic field. They were taken in 1924 by Professor Kapitza, a famous Russian physicist for whom the Royal Society built the Mond Laboratory at Cambridge.



Fig. 494

The α Particle

During the early years of the present century Rutherford and his colleagues devised experiments to help them find out more about the α particle. By 1903 they had deflected α particles by electric and magnetic fields. The direction of the deflection showed that the particles carried a positive charge. Deflection experiments also showed that the ratio of the charge to the mass of the α particle was about twice that of the hydrogen nucleus.

In 1908 Rutherford and Geiger found that the charge on the α particle was twice the size of the electronic charge, but of course opposite in sign.

If we assume that the charge (Q) on a hydrogen nucleus is 1 unit and the mass (m) is 1 unit, we have

$$\frac{Q}{m} \text{ for hydrogen} = 1$$

$$\frac{Q}{m} \text{ for } \alpha \text{ particle} = 2$$

As, however, the charge (Q) on the α particle is also 2 units, the mass (m) must be 4 units. The α particle has therefore 2 (electronic) units of positive charge and 4 (proton) units of mass.

Could this mean that the α particle was really a helium nucleus? In 1909 Rutherford and Royds demonstrated that it was. To do this they devised a piece of equipment in which they captured some fast-moving α particles.

They used radon gas as a source of α particles, and enclosed it in a glass tube fitted with a thin window through which the particles could pass. This tube was fixed inside a much thicker glass tube through which the α particles could not escape (Fig. 495). The space inside the thicker tube was evacuated, and the apparatus was left for several days to allow α particles to pass through into this space.

Rutherford and Royds then pumped mercury into the tube so that its contents were compressed into a discharge tube. When a large voltage was then applied to the electrodes and the discharge

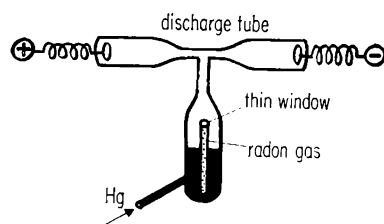


Fig. 495

examined with the aid of a spectrometer, the helium spectrum was observed. The α particles had each collected a couple of stray electrons and changed into helium atoms. This was accepted as conclusive evidence that α particles are helium nuclei.

Professor Blackett photographed collisions between α particles and helium atoms in a cloud chamber, and showed that the angle formed by the two tracks after the collision was 90° (Fig. 496 and Book 3, page 85).

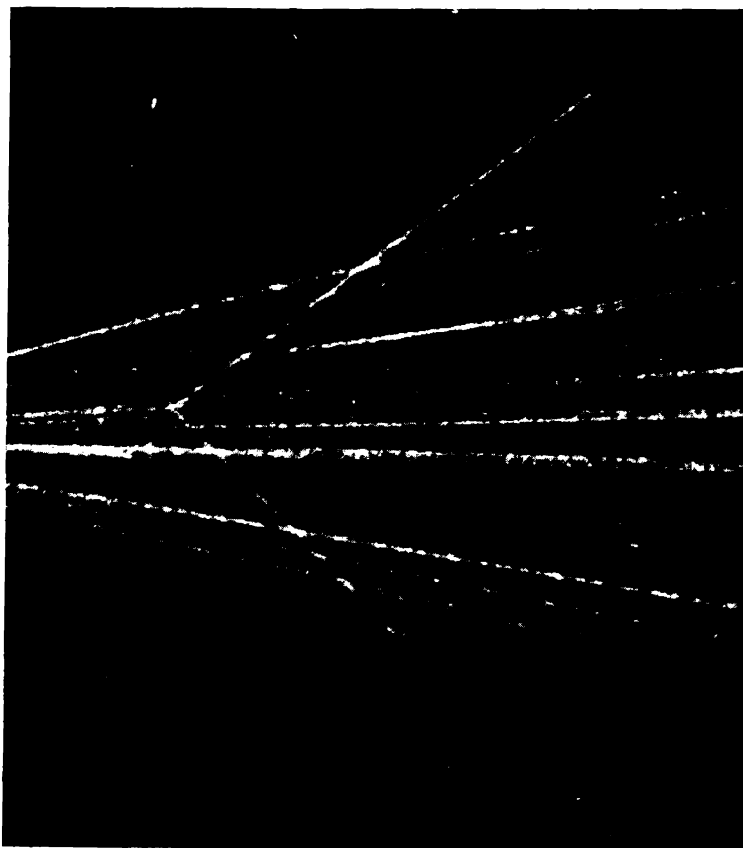


Fig. 496

If we assume that momentum and kinetic energy are both conserved in such a collision, we can show that the mass of the α particle must be the same as the mass of the helium atom. *Try it! Hint: draw a vector triangle of velocities assuming the masses to be the same, that is, $\vec{V} = \vec{V}_1 + \vec{V}_2$ and $V^2 = V_1^2 + V_2^2$. (2).*

Alpha Activity

To sum up then, we can say that α particles are relatively heavy, slow and positively charged. They are emitted in a random way and have a range of a few centimetres in air, their energy being gradually dissipated by ionising collisions with air molecules. The

range is therefore a measure of the energy of the particle. Alpha particles produce strong ionisation and are stopped by a sheet of paper and most other solids.

Each α particle is a helium nucleus (2 protons + 2 neutrons) and is about 8000 times as heavy as an electron. Its speed may be about 5 per cent of the speed of light.

Americium-241 and radon-220 emit only α particles; that is, they are pure α sources.

Alpha particles may be detected by

- (i) an ionisation chamber and a d.c. amplifier or pulse electro-scope,
- (ii) a solid state detector,
- (iii) a gold leaf electroscope,
- (iv) a spark counter,
- (v) a cloud chamber,
- (vi) a *thin*-windowed Geiger tube and a scaler or ratemeter,
- (vii) a photographic plate.

Beta Behaviour

In 1900, Marie and Pierre Curie first showed that β particles carry a negative charge. The charge-to-mass ratio of the β particle was later found to be similar to that of the electron, and it was concluded that β particles were in fact very fast moving electrons. They are relatively light and swift. They normally carry a negative charge. Their range in air is much greater than that of α particles, but they produce much less ionisation.

Beta particles have a wide range of energies, but the more energetic particles may travel near the speed of light, for example around 2.5×10^8 m/s.

They are much more easily deflected by a magnet or an electric field than are alpha particles, and they may be stopped by a few millimetres of aluminium.

Strontium 90 is a pure β source.

Beta particles may be detected by

- (i) an ionisation chamber and d.c. amplifier,
- (ii) a cloud chamber,
- (iii) a Geiger tube and a scaler or ratemeter,
- (iv) a photographic plate.

Gammas Galore

These were first discovered by the Frenchman Paul Villard in 1900. They are the most penetrating of all the radiations, and several centimetres of lead are needed to stop them. Because of their penetrating power gamma rays constitute the most serious *radiation hazard* to human beings.

Gamma rays show interference and diffraction effects, and are now known to be electromagnetic waves similar to X-rays but having shorter wavelengths of the order of 10^{-11} metres. The actual wavelength depends on the radioactive substance emitting

them. Like other electromagnetic radiations, they travel at 3×10^8 m/s.

Gamma rays cannot be bent by magnetic or electric fields; that is, they do *not* consist of charged particles. They are perhaps best thought of as tiny bursts of waves, or *photons*.

Cobalt-60 is a pure γ source.

Gamma rays may be detected by

- (i) a cloud chamber: faint twisted tracks,
- (ii) a Geiger tube and a scaler or ratemeter,
- (iii) a photographic plate.

Name	Nature	Charge (electronic units)	Mass (nucleon units)	Velocity	Stopped by	Penetration (arbitrary units)
Alpha particle	Helium nucleus ${}^4_2\text{He}$	+2	4	5% that of light	Sheet of paper	1
Beta particle	Electron ${}_{-1}^0\text{e}$	-1	$\frac{1}{1836}$	90% that of light	A few millimetres of aluminium	100
Gamma radiation	Bursts of electromagnetic radiation of very short wavelength	0	0	Velocity of light	Many centimetres of lead	10,000

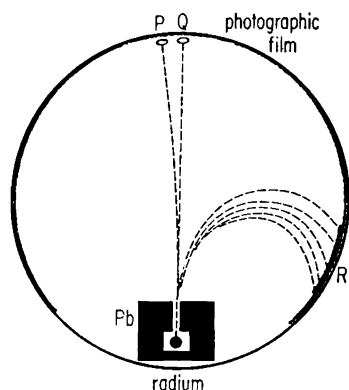


Fig. 497

Problem 3. A radium source emits α and β particles and γ rays. If such a source is placed in a lead block so that a parallel beam of radiation is emitted, this beam can be split up into three parts by a strong magnetic field (Fig. 497). The south pole is under the paper and you are to imagine a north pole placed over the diagram so that the field lines run into the paper. P, Q and R represent marks on a photographic film. What is responsible for each of these marks?

Perpetual Motion?

Is a radioactive material a continuous source of energy? Will it continue shooting out particles for ever? The source you used in the cloud chamber certainly appears to do this and there is no apparent change after months of use. Careful measurements, however, show that as they emit radiations all radioactive materials gradually lose their activity, which is the rate at which they throw out particles or rays. With some materials most of the activity has disappeared in a fraction of a second; with others it takes millions of years.

It is often very difficult to say when a substance has lost *all* its activity, but it is comparatively easy to find out how long it takes for the activity to fall to half its value. This period of time is the *half-life*.

A-Z

The nuclei of radioactive atoms are unstable. If a nucleus emits an α particle, the remaining nucleus will have a different mass and a different charge. The number of nucleons in a nucleus is called the *nucleon number* or mass number (A) and is written as a superscript. Helium, for example, has 4 nucleons and is written symbolically ${}^4\text{He}$.

The number of protons in a nucleus is called the *proton number* or atomic number (Z) and is written as a subscript. Helium has two protons in its nucleus and is written symbolically ${}_2\text{He}$. A helium atom is therefore represented by the symbols ${}_2^4\text{He}$ or in some books ${}_2\text{He}^4$.

Alpha Emission

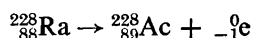
When a nucleus ejects an α particle, its nucleon number (A) is reduced by 4 and the proton number (Z) by 2. For example, when thorium-232 emits an α particle it changes to radium-228. This is called a *radioactive transmutation*.



The new material is christened the *daughter product*, implying elements of unpredictability and change! The daughter herself may also be unstable and explode without warning to form a 'grand-daughter' atom. This process continues until a stable atom is produced.

Beta Emission

If an atomic nucleus ejects a β particle, one of its neutrons has changed to a proton and so the proton number (Z) increases by one. The total number of nucleons (A) is not, however, altered. The disintegration of the above daughter nucleus of radium 228 illustrates this transmutation. Actinium is formed.

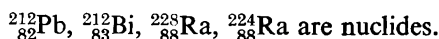


Gamma Emission

Often a daughter nucleus is left in an excited state and the rearrangement of the nucleons, which takes place in about 1 microsecond, releases a high energy photon of electromagnetic radiation, that is, a γ ray.

Nuclides

It is possible for the nuclei of different elements to have the same mass number (for example, ${}_{82}^{212}\text{Pb}$ and ${}_{83}^{212}\text{Bi}$), and for the nuclei of the same element to have different mass numbers (for example, ${}_{88}^{228}\text{Ra}$ and ${}_{88}^{224}\text{Ra}$). When we specify a particular A and Z for an element we refer to it as a *nuclide*.



Radioactive nuclides are called *radionuclides*.

If one nuclide has the same proton number (Z) as another, they are called *isotopes of that element*. They come in the 'same place' in the periodic table (*isos* = same, *topos* = place). For example, $^{223}_{88}\text{Ra}$ and $^{224}_{88}\text{Ra}$ are isotopes of radium and have the same chemical properties since they have the same electronic configuration. They are the same 'outside' but different 'inside'. Radioactive isotopes are called *radioisotopes*.

Here is a chart of radioactive disintegrations in which a series of new nuclides are being formed. The times stated indicate the approximate half-lives of the radionuclides. Notice the type of change which takes place when an α particle is ejected, and the completely different kind of change which takes place when a β particle is ejected. Notice also the range of half lives.

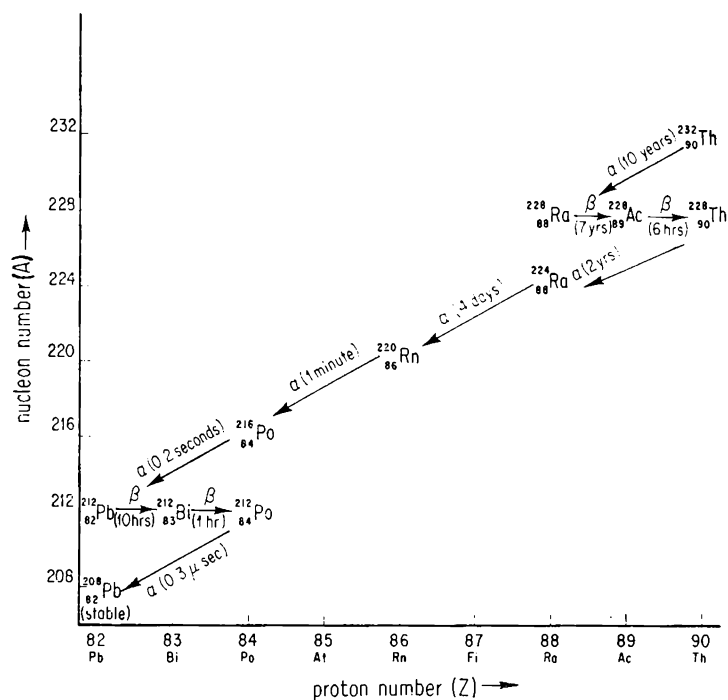


Fig. 498

Problems

4. Describe how you would show experimentally that radium emits three different kinds of radiation.

5. How would you investigate the radiation from a luminous dial on a wrist watch?

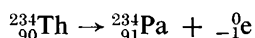
6. You are told that americium-241 emits only α particles. How would you check that it does not emit β particles or γ rays? How could you find out if the α particles affect a photographic plate?

7. Strontium-90 is a pure beta source. How would you test this statement?

8. How would you show that cobalt-60 emits γ radiation but not α or β particles?

9. Beta particles are stopped equally well by a few centimetres of air or a few microns of aluminium. Explain this.

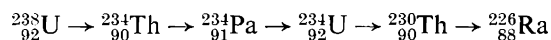
10. Describe the following nuclear reactions



11. How would the behaviour of α and β particles and γ rays differ in a strong electric field?

12. There are 3.7×10^{10} disintegrations per second from 1 gramme of radium. What would be the rate of disintegration from 0.1 grammes of radium? State this rate in curies.

13. Here is part of the uranium series.



State what particles are emitted at each stage.

14. If an atom has a mass number A and an atomic number Z , state the number of electrons, protons and neutrons in the atom. State the mass and atomic numbers for the daughter nucleus after (a) an α particle or (b) a β particle has been ejected.

15. To clean the inside of a pipe line a small gadget called a 'go-devil' is used. It consists of a cylinder surrounded by rubber washers and wire brushes. Compressed air or water pressure is used to push it through the pipe, and it is not unusual for one to get jammed. To save time in attempts to locate the position of a lost go-devil, a radioactive marker is fixed in its central core. State what type of radiation it would have to emit and why. Name a suitable source. How might you set about looking for the jammed go-devil?

16. The intensity of γ rays radiated from a point source varies inversely as the square of the distance from the source: that is, γ rays obey the inverse square law. If a ratemeter reads 200 when the G-M tube is 60 centimetres from a cobalt-60 source, what will it read when it is (a) 120 cm, (b) 30 cm from it?

17. Four radioactive sources are labelled P, Q, R and S respectively. An electroscope, spark counter, thick-windowed Geiger tube and an ionisation chamber are used to detect the radiations. Can you determine from the following information what the sources are emitting?

Electroscope	P and S discharge it Q discharges it very slowly R does not discharge it
Spark counter	P and S cause sparks Q and R do not cause sparks
G-M tube	P produces no effect Q, R and S produce counts
Ionisation chamber	P and S produce ionisation Q produces slight ionisation R produces no ionisation

Absorption*Paper stops radiation from P**2 mm aluminium stops radiation from Q**2 cm lead stops radiation from R**Some of the effects of S are stopped by paper, others by 2 mm of aluminium and others by 2 cm of lead***Magnetic deflection***All of the radiation from Q and some of the radiation from S is deflected by a magnetic field. A strong magnetic field deflects the radiation from P very slightly in the opposite direction. Radiation from R is not affected.*

18. Which radiations would penetrate the door of a storage cupboard containing radium sources? How could you design a cupboard to reduce this to a safe level?

Half-life

Our experiments with radioactive substances have shown that particles and rays are emitted in a haphazard or *random* way. Nevertheless, if a large enough number of atoms are disintegrating, the average number of disintegrations per second can be predicted with reasonable accuracy. The whole insurance business is based on probabilities of this kind. For example, it would be quite impossible to say whether or not any particular car driver would be involved in an accident in a given year, yet a company with which 100,000 are insured can make a fairly close estimate of the number of accident claims they may expect. If 200,000 cars were insured with the company, they would expect twice as many claims. If 300,000 were insured they would expect three times the number of claims, and so on.

When a radioactive substance disintegrates, the activity (that is, the number of disintegrations per second) depends only on the number of radioactive nuclei present. With double the number we have double the activity; three times the number, three times the activity, and so on. The half-life of a given nuclide is defined as the time taken for half of the number of nuclei to disintegrate. As, however, this means that the activity is also reduced to half its value, the half-life is equal to the time taken for the activity to drop to half its value. This is illustrated in the following analogues.

Demonstration 12.15

(i) The apparatus can be easily constructed from a plastic lampshade with ten 4 mm holes drilled in it at random. It is driven by an electric motor N_{150M} as shown in Fig. 499.

Weigh out about 200 grammes of uniform lead shot and pour it into the lampshade. Switch on the motor, and once the drum is rotating at a steady speed, place an empty beaker under the spout to collect the shot ejected. Leave it there for 15 seconds and then replace it with another empty beaker. Continue this process so that you have a number of beakers containing the shot ejected in successive 15-second intervals.

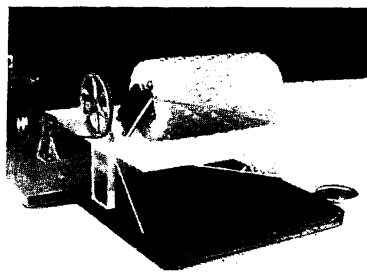


Fig. 499

If the contents of each beaker are poured into a glass tube (Fig. 500) the change in the rate of ejection can be seen.

Alternatively, find the mass of lead shot in each beaker and plot a graph showing how the activity (rate of ejection) varies with time. The graph is called an *exponential curve*, the graph of natural decay. From the graph find how long it takes for the activity to fall to half its original value.

(ii) This analogue can be extended to produce graphs of activity versus mass left in the drum and mass left versus time. In what way does this analogue differ radically from radioactive disintegration?

Experiment 12.16. Paint one face black on each of 400 wooden cubes. Throw the cubes and remove all those with their black faces uppermost. Repeat the process with the remainder and continue until all the cubes have been removed.

Plot a graph of the 'cubes removed' against the 'number of the throw.' What kind of graph is produced by your results? What is the half-life period in 'number of throws'?

In what way is this experiment not a good analogy of radioactive decay?

There are two important practical difficulties involved in measuring half-life. If we start with 16 grammes of a particular radio-nuclide which has a half-life of 6 hours, we will find that its mass is still very nearly 16 grammes after that length of time has elapsed! The daughter nuclides are not 'weightless'. Fig. 501 shows the decay of actinium-228.

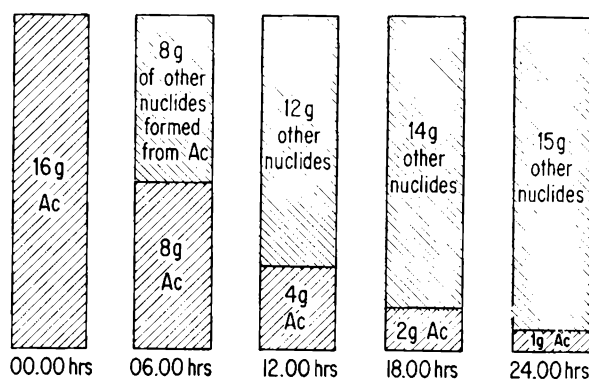


Fig. 501

The actual loss of mass due to the emission of particles or rays is very small indeed. For example, 165,000 disintegrations of cobalt-90 carry off a mass equal to only one atom of cobalt. Weighing a disintegrating radioactive substance will certainly not help us to find its half-life.

Secondly, if we imagine that we can avoid this difficulty by measuring the *activity*, we may still be disappointed. The daughter nuclei may also be radioactive so that we are measuring the radiation from two or more nuclides. We can, however, obtain a reasonable estimate of the half-life of a nuclide by finding the time

taken for its activity to fall to half its value if (i) the daughter products are not radioactive, or (ii) the experiment is designed in such a way that the detected radiations from the daughter products are small enough to be ignored.

If you study the radioactive series in Fig. 498, you will see that it would not be easy to investigate the half-life of many of them. In fact, radon-220 (or emanation-220 or thoron) is the only one we could readily study in a school laboratory. Fortunately it is a radioactive gas which is fairly easily obtained from thorium hydroxide or thorium carbonate. Radon-220 is an α emitter, as is its daughter nuclide, polonium-216. As the latter has a half-life of 0.2 seconds, any α particle detector will record both radiations. Such a detector will not, however, record the β particles emitted from the grand-daughter nuclide, lead-212, which has a half-life of about eleven hours. In the following experiments we will use a cloud-chamber and an ionisation chamber to investigate the half-life of radon-220. Both instruments are more sensitive to the α than to the β particles.

Demonstration 12.17. Set up a diffusion cloud chamber using about 1 cm³ of alcohol in the felt ring and 10 cm³ of dry ice in the lower compartment. Remove the radioactive source and puff in a *small* quantity of radon-220. Insert a cork in place of the normal source.

Study the α particle tracks, noting how the number produced varies with time. Can you estimate how long it takes for the number of tracks to be reduced to half? The photograph in Fig. 503 was taken 60 seconds after Fig. 502. Can you explain the occasional V-shaped track? Refer to the radioactive series in Fig. 498.

Warning: Do not open the cloud chamber for at least an hour after conducting this experiment.

Demonstration 12.18. Attach an ionisation chamber to a 100 volt battery and a d.c. amplifier₁₀ fitted with a 10¹¹ ohm input resistor. Couple a squeeze bottle to the chamber and puff in a little radon-220 until the meter reads just over full scale. The meter reading is proportional to the ionisation current, and this is proportional to the rate at which the radon nuclei are disintegrating. The meter reading is therefore an indication of *activity*.

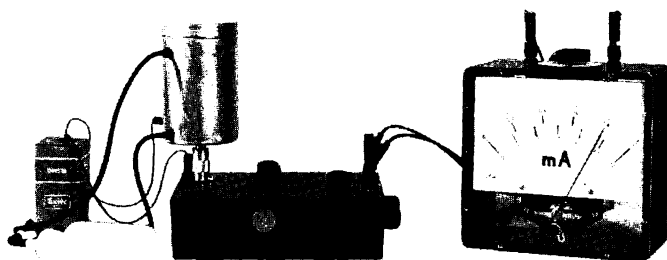


Fig. 504

When the meter reading returns to full scale, start taking readings every 15 seconds and plot a graph of activity against time. From this find the half-life of radon-220.

(A pulse electroscope can also be used to indicate the activity.)

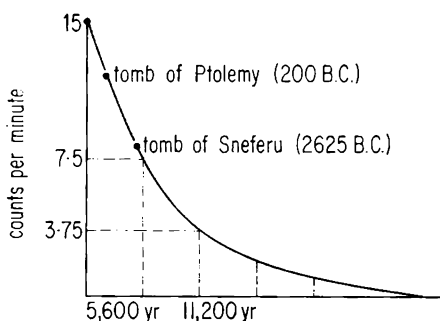
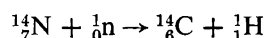


Fig. 505

Tomb Time

Cosmic ray neutrons can react with the atoms of nitrogen present in the atmosphere to produce the radionuclide carbon-14



In the form of carbon dioxide some of this radioactive carbon is absorbed by living plants for use in photosynthesis. When the plant dies no more carbon dioxide is absorbed, and the radioactive carbon present emits β particles and decays with a half-life of about 5600 years.

It has been found that one gramme of carbon from a living plant decays at a rate of 15 disintegrations per minute, so that 5600 years after the plant dies this should have dropped to 7.5 disintegrations per minute. By measuring the count rate produced by the carbon in archaeological specimens of wood or charcoal, the time which has elapsed since the original plant died can be estimated. This is called *carbon dating*.

When Dr. Libby, an atomic scientist in Chicago, first thought of the possibility of using this method of dating, he secured from a museum a piece of wood which was part of an Egyptian ship found buried near the Pyramids. Historians thought it was about 3800 years old. Dr. Libby analysed it and his results suggested that the wood was 3620 years old! Carbon dating suggests that the famous Dead Sea Scrolls were written at the beginning of the Christian era, while charcoal from Stonehenge shows that it was built 2000 years before that. Fig. 505 shows an exponential decay curve for carbon-14 with the count rates obtained from two tombs, each of a known age, superimposed.

The age of certain rocks has been estimated by assuming that the uranium-238 present in them was formed at the same time. As uranium-238 decays with a half-life of 4500 million years and eventually turns to lead, the relative quantities of uranium and lead present in a sample of rock enable its age to be computed.

Problems

19. The half-life of $^{131}_{53}\text{I}$ is 8 days. Starting with 1 gramme of this nuclide, what mass will have decayed in 32 days? Has this quantity of matter disappeared? If a β particle is emitted during the decay process, what will be the proton number (Z) of the daughter atom?

20. If radium has a half-life of 1,600 years, what fraction of the original mass of radium will be left after 9600 years? How will the total mass left compare with the original?

21. A radionuclide has a half-life of 2 hours. What percentage of the original activity will be present after 10 hours?

22. 226 grammes of radium-226 ($^{226}_{88}\text{Ra}$) contains Avogadro's number (6×10^{23}) of atoms. Starting with 1 milligramme of radium, how many atoms will disintegrate in 1620 years, its half-life period?

23. The activity from a radionuclide was measured at 3 day intervals. From the following readings plot a graph and find the half-life.

Time (days)	0	3	6	9	12	15
Activity	130	85	56	37	24	15

24. A man borrows £1000 interest free and pays back 20 per cent of his debt each year. Draw a graph showing how his rate of repayment varies with time. When will this rate have dropped to half its original value? What is the form of the graph you have drawn?

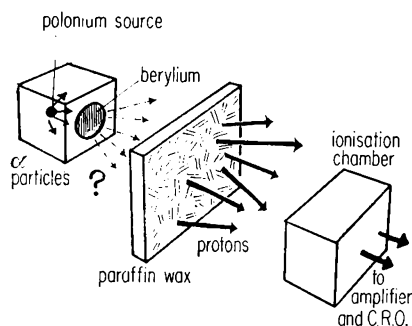


Fig. 506

Artificial Radioactivity**Chadwick Discovers the Neutron**

Several scientists had found that when beryllium was bombarded with alpha particles a strange type of radiation was produced. The French physicist Joliot and his wife Irene Curie (daughter of the discoverers of radium) used an ionisation chamber to detect this new radiation. When they placed a slab of paraffin wax in its path they found that the ionisation current *increased*! They were able to show that this effect was produced by the ejection of *protons* from the paraffin wax. The Joliot-Curies suggested that the unknown radiation, which was not deflected by a magnetic field, might be high energy γ rays.

In 1932 Chadwick repeated this experiment, and pointed out that, if it is assumed to be γ radiation, then energy and momentum were not conserved. Chadwick could, however, get his sums right if he assumed that the rays from the beryllium consisted of uncharged particles with the same mass as protons. He thought that each of these particles might consist of a proton and an electron; a combination suggested twelve years earlier by Rutherford, who proposed the name *neutron*. The neutron is now regarded as a fundamental particle in its own right rather than a combination of a proton and an electron. It passes through atoms easily and leaves no trace in a cloud chamber, but, if it makes a direct hit on an atomic nucleus, charged particles can be released which will produce tracks. As the neutron is uncharged there is no electrostatic repulsion between it and an atomic nucleus. It is, therefore, an ideal nuclear bullet to fire at nuclei.



Fig. 507

Anderson Discovers the Positron

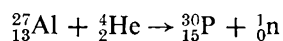
In the year Chadwick discovered the electron, Dr Carl Anderson discovered the positive electron or positron. Working in the Institute of Technology in California, he took a cloud chamber photograph of a cosmic ray which had penetrated a lead plate and entered a strong magnetic field. The track was identical with those produced by electrons, but it curved the other way! Fig. 507 shows a cloud chamber photograph of the tracks of a positron and an electron after being formed simultaneously from a γ -ray photon. Matter created from energy! The γ -ray does not produce ionisation and its path is therefore invisible.

The First Artificial Radionuclide

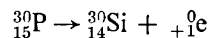
The Joliot-Curies continued bombarding light elements with α particles. In one experiment they bombarded aluminium and found that neutrons were produced. When they removed the α source the neutron emission stopped. This was not particularly exciting or unexpected!

They then found that something was coming from the aluminium which activated a Geiger counter. When the α source was removed the counter went on counting. Two and a half minutes later the count rate had fallen to half, and two and a half minutes after that it was down to a quarter. The year was 1934, and for the first time in history a man-made radioactive substance had been identified.

When the aluminium was analysed, the source of the radioactivity was found to be a radioisotope of phosphorus, phosphorus 30. For the bombardment process the equation is



When the phosphorus disintegrates it emits a positron (or positive β particle) and an isotope of silicon is formed. The equation is



For producing the world's first artificial radionuclide (radioisotope) the Joliot-Curies received in 1935 the Nobel Prize in Chemistry. In the same year the Nobel Prize in Physics went to Chadwick for his discovery of the neutron.

During the last 30 years more and more radionuclides have been produced, until at present about 1500 are known. They include radioactive forms of every known element. Radionuclides are now produced by placing a stable element in a nuclear reactor where it is bombarded by neutrons, or by bombarding the nucleus with a fast-moving charged particle from an accelerator such as a cyclotron or linac.

Radionuclides Produce Miracles

Early in the present century, Professor Georg von Hevesy was staying in a boarding house in which he suspected that the stew was sometimes made from scraps left over from an earlier meal. One day he added a little radioactive lead to the food left on his plate, and when the inevitable stew was served he surreptitiously



Fig. 508 (a)



Fig. 508 (b)



Fig. 508 (c)

took a sample and tested it for radioactivity. In this, the first recorded use of a *radioactive tracer*, the Professor's worst fears were confirmed!

Britain, in 1948, became the first country to set up a manufacturing centre for artificial radionuclides. Many of them have to be handled by remote control from behind lead or concrete walls (Figs. 508 (a) (b) and (c)).

Although such nuclides have been in common use for only a few years, a whole library of books could already be written on the mysterious and exciting ways in which they are now being put to work.

They kill cancerous growths in the body and help doctors to diagnose other disorders. Seeds exposed to them can germinate

and grow into plants with unusual and often improved characteristics. Their rays kill bacteria and are therefore used to sterilise food and drugs. Tinned foods have been found to keep fresh longer after such irradiation. Dressings, thermometers, hypodermic needles and syringes can be cold sterilised *after* they have been packed in airtight polythene containers.

Radionuclides are used in industry to detect flaws, control quality, eliminate unwanted static electricity, and to measure the thickness and volume of materials. Radioactive plutonium was chosen to power the electronic equipment in an American navigational satellite launched in 1961. Signals are still being received from it after hundreds of millions of miles of travel.

Irradiating polythene causes a cross-linkage of molecules which strengthens the material considerably.

A few applications from medicine, farming and industry are illustrated in the accompanying photographs.

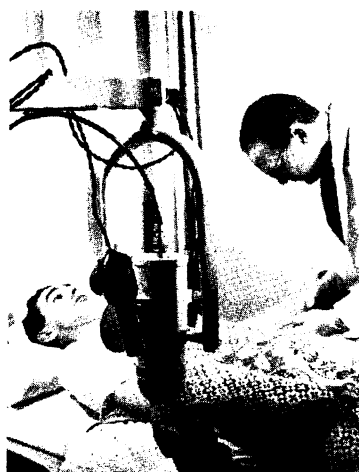


Fig. 509

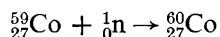


Fig. 510

The time taken for blood to find its way from one wrist to the other is being investigated in Fig. 509. A radionuclide is injected into the patient's left wrist and its arrival at the other will be detected by the G-M tube above it.

The radiation picture in Fig. 510 was constructed from seven scans of a man's body. The spots indicate the presence of radioactive atoms and the bright cluster in the lung region indicates an abnormal condition. Radioactive scanning of this kind often reaches areas inaccessible to X-rays.

When cobalt is bombarded by neutrons in a nuclear reactor, one ordinary nucleus can capture a neutron and become radioactive.



Cobalt-60 has hundreds of uses today, but the destruction of cancerous growths or tumours can be one of the most valuable. The γ rays which this nuclide emits have a destructive effect on healthy living tissue, but they have an even greater effect on diseased tissue. If the cancer is right inside the body, a beam of γ rays of lethal intensity for the tumour would also damage other parts of the body through which they passed. This difficulty has been overcome in an ingenious way. The cobalt source is made to rotate in a circle in such a way that the beam of γ rays it produces is always directed towards the centre. The patient is then placed so that the tumour is exactly at the centre of this circle. As the source rotates the radiation dose is very great at the centre where it is needed, but not sufficiently high elsewhere to do any damage.

Caesium-137, obtained from the waste products of atomic reactors, is also often used in this treatment of cancer (Fig. 511).

In the Southern United States the screwworm fly has been a perpetual scourge of cattle. To control this pest thousands of millions of male flies have been sterilised by subjecting them to the γ rays from cobalt-60. These flies have then been released in infested territory. When they mate with a female screwworm the eggs are sterile. Cattlemen believe that screwworms can be eliminated in this way.

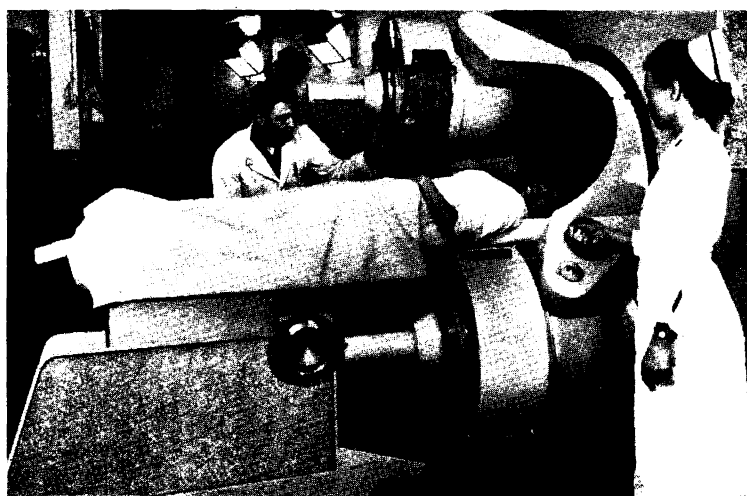


Fig. 511

The ionisation of air by radioactivity is used in the textile industry and in paper mills to prevent the build-up of large-scale static charges on materials. These charges on fabrics attract dust and the material soon becomes dirty. To remove the charges a radionuclide may be fixed above a loom. Fire danger is also reduced and the loom can be made to work faster. It has been found that smoother textiles can be produced when the charges are allowed to leak away in this way.

Variations in the absorption of β rays by different thicknesses of material can be used to determine thickness. In Fig. 512 a radionuclide is being used to measure the thickness of paper.

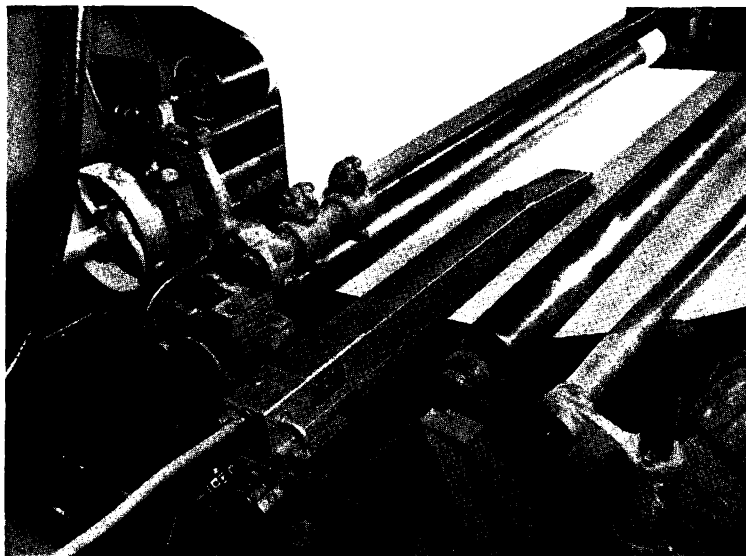


Fig. 512

To measure the wear of a piston ring in a car engine, the ring is first made radioactive. When the engine is running radioactive fragments will be rubbed off and carried away in the oil. The oil may then be pumped to a radiation detector in the back of the car before returning to the engine. The amount of radiation detected gives an indication of the piston ring wear. The wear produced at different speeds can easily be determined by this method.

In Fig. 513, gears, made radioactive by irradiation in the BEPO reactor at Harwell, are being fitted to a car back axle. The wear will be measured by the debris dispersed in the lubricating oil.

At the Atomic Energy Research Establishment at Harwell, methods have been developed for converting the energy available from radionuclides directly into electricity. In the RIPPLE generator (*radioisotope powered prolonged life equipment*), a core of radioactive strontium titanate is surrounded by a mosaic of thermoelectric elements. These are really thermocouples utilising modern semiconductors. As the strontium-90 disintegrates, the β particles carry enough energy to produce an output of a few watts. The present efficiency of such a generator is extremely low, but its great advantage is that it can be guaranteed to produce a continuous unattended supply of electricity for about ten years.

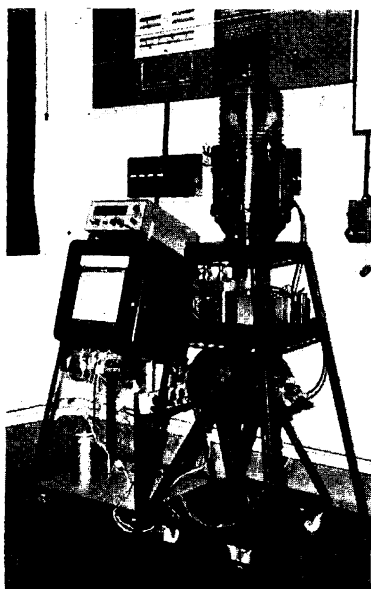


Fig. 514

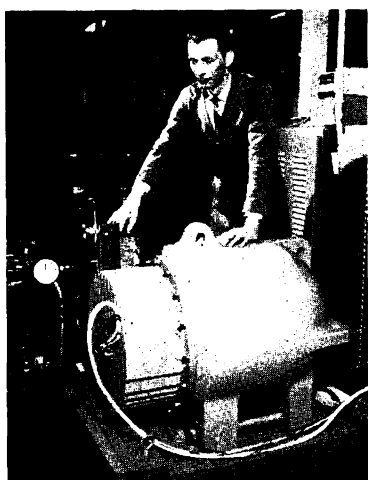


Fig. 515

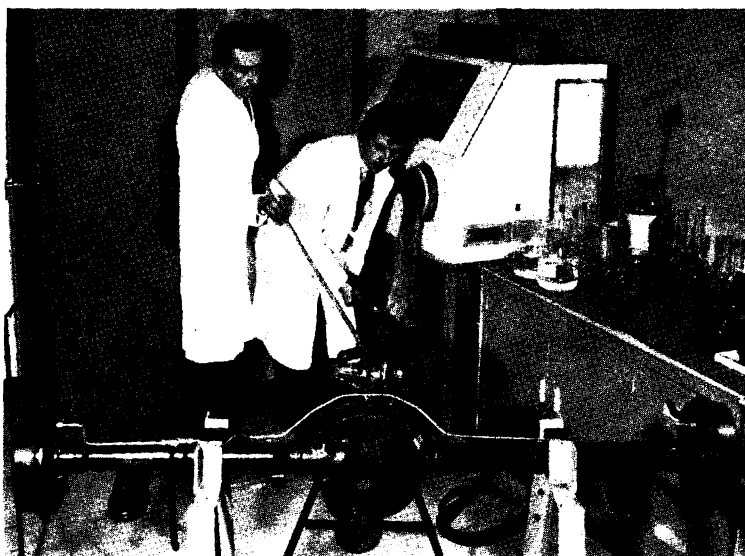


Fig. 513

It should have many applications in unmanned weather stations, navigation beacons, repeater stations and satellites. Fig. 514 shows a flashing navigation light powered by a 1 watt RIPPLE generator.

In America a 5 watt generator using strontium-90 has been marketed. The manufacturers claim that it will operate for five years without refuelling (Fig. 515). The United States Atomic Energy Commission is working on a heart 'pacemaker' powered by plutonium-238. It is hoped that this SNAP (system for nuclear auxiliary power) equipment will weigh only 300 grammes and operate without attention for at least five years. It will contain electronic circuits requiring about 50 microwatts to deliver small electric shocks to the heart 70 times a minute.

Problems

25. Can you suggest a way of sterilising a hospital blanket using a radionuclide? What precautions would you take? What advantages would this have over steam sterilisation?

26. When handling radioactive materials workers wear badges containing photographic paper. Why is this? Name some of the precautions taken in laboratories where radionuclides are used.

27. When radioactive phosphorus ($^{30}_{15}\text{P}$) decays, it emits a positron. Will the daughter nucleus have the same mass number? Will it be another isotope of phosphorus?

28. Distinguish between

- atomic weight and atomic number,
- isotope and nuclide,
- artificial and natural radionuclide,
- atomic mass and mass number,
- α and β particles,
- electron (negatron) and positron.

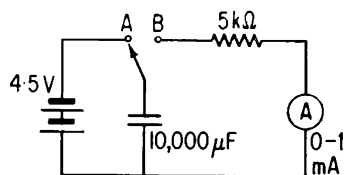


Fig. 516

29. Einstein's famous equation $E = mc^2$ relates energy in joules to mass in kilogrammes. The speed of light (c) is 3×10^8 m/s. Using the following approximate figures find the energy changes

(a) when a proton is converted to a neutron plus a positron (positive electron) and

(b) when a neutron is converted to a proton plus an electron.

The rest mass of an electron equals 9×10^{-31} kg

The rest mass of a proton equals $16,726 \times 10^{-31}$ kg

The rest mass of a neutron equals $16,749 \times 10^{-31}$ kg

30. Nimrod is a proton synchrotron at Harwell. It accelerates protons which are held in closed orbits by a ring-shaped electromagnet (Fig. 542). The protons make a million orbits and travel 80,000 miles in less than a second. In doing so they gain an energy of 7 GeV (7×10^9 electron volts). Nimrod was designed to produce a proton beam of 10^{11} protons per second. What is the power of such a beam? ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$).

Optional Extra

The rate at which a capacitor (C) is discharged through a resistor (R) is another example of *exponential decay*. As the current (I) through the resistor is proportional to the p.d. (V) across the capacitor and the p.d. is proportional to the charge (Q) on the capacitor ($V = Q/C$) we have—

$$I = \frac{V}{R} = \frac{Q}{CR} = kQ \text{ where } k \text{ is a constant} = \frac{1}{CR}.$$

$$\text{As } I = \frac{\Delta Q}{\Delta t}$$

$$\text{we have } -\frac{\Delta Q}{\Delta t} = kQ$$

The rate of change of charge (i.e. the current) is proportional to the charge left. The negative sign indicates that the charge is getting less as time passes.

The constant k is called the *decay constant* and $\frac{1}{k}$ is related to the half life $t_{\frac{1}{2}}$ (i.e. the time taken for the capacitor to lose half its charge) by the equation

$$\frac{1}{k} = CR = 1.4t_{\frac{1}{2}}$$

(C in farads, R in ohms, $t_{\frac{1}{2}}$ in seconds.)

As $V \propto I \propto Q$, we will get an exponential curve if any one of them is plotted against time. The circuit of Fig. 516 is suitable.

In the radiation case the rate at which particles are ejected ($\frac{\Delta N}{\Delta t} = \text{activity}$) is proportional to the number of radioactive particles left (N).

$$\text{i.e. } -\frac{\Delta N}{\Delta t} = \lambda N$$

Both activity and the number of radioactive nuclei left when plotted against time will give an exponential curve.

$$\lambda \text{ is the decay constant and } \frac{1}{\lambda} = 1.4t_{\frac{1}{2}}$$

Rutherford and Soddy first propounded the 'Law of radioactive change' in 1903. It may be stated thus: 'the number of disintegrations per second at any time is proportional to the number of radioactive atoms present at that time'.

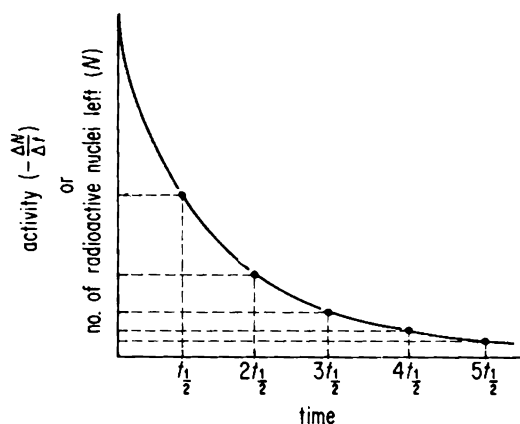


Fig. 517

Summary

When a radionuclide disintegrates it can emit α , β or γ radiation.

α particles are positively charged helium nuclei.

β particles are negatively charged electrons.

γ rays are short bursts of high frequency electromagnetic radiation.

Most α particles are absorbed by a sheet of paper.

Most β particles are absorbed by 2 mm aluminium.

Most γ rays are absorbed by 2 cm lead.

One of the main effects of these radiations is *ionisation*.

The half-life of a radionuclide is the time taken for half its atoms to disintegrate. This is also the time taken for the activity to drop to half its value. The total mass, including the daughter products, is not altered appreciably in this time.

Artificial radionuclides are used in industry, agriculture and medicine. One way of making a substance radioactive is to bombard it with neutrons in a nuclear reactor.

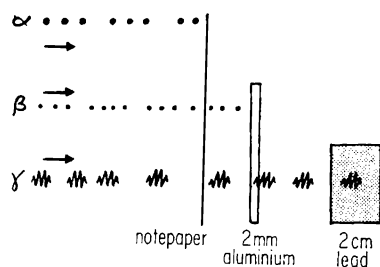


Fig. 518

Visual Aids

Charts: Radioactivity₃₀ C644/2.

Filmstrips: Rays from Atoms₂₉ 08.0027.

16 mm Films: Rays from Atoms₂₉ 20.4598.

Discovery of Radioactivity₃₁ 2DC.2785.

Isotopes₃₁ 2DC.2090.

Radioactivity₃₁ 2DC.2876.

Radioactivity₃₂ S22.

Eye for Isotopes₃₆ 1589.289E.

Introduction to Radioactivity₃₇ (for teachers).

Further Experiments on Radioactivity₃₇ (for teachers).

Quack, Quanta, Quark

CHAPTER 13

Structure and Behaviour

Throughout this course we have been continually asking two questions, 'What is it made of?' and 'What does it do?' These questions are of course interrelated. We have built up theories of structure from observations of behaviour, and we have attempted to explain new behaviour in terms of accepted theories of structure. In the early part of the course our studies of such things as Brownian movement and crystal structure supported the idea that matter is *grainy*, that is, a sub-microscopic 'sand' rather than a 'treacle'. The kinetic theory of gases was based on the assumption that molecules behave like minute elastic balls which obey Newton's Laws of Motion. Boyle's Law and Charles' Law were predicted theoretically on this basis.

To explain the results of experiments in electrostatics and current electricity, tiny charged particles were postulated, and later work on the ionisation of gases by flames, X-rays and radioactive particles supported this hypothesis. We saw that, when Millikan used his ingenious oil drop experiment to measure the fundamental unit of charge, the electron became 'respectable' . . . which was just as well for the development of the thermionic valve! Spectral bands produced by an excited atom were then discussed in terms of its electrons jumping from one energy level to another.

Cloud chamber tracks produced by charged particles in flight were interpreted on the assumption that *momentum* was conserved. Nuclear reactions were described on the basis of the 'nuclear atom' in which *charge* (Z) and *mass* (A) or its equivalent energy were conserved. In fact, in all branches of physics we have continually been meeting *conservation* of such things as mass/energy, momentum and charge.

Perhaps you would now like to write down on a sheet of paper a list of all the basic principles you have met in this four-year course.
(1)

We will conclude with a brief historical survey of some of the more important events which led to the development of the modern concept of the atom and to nuclear science as it is known today. This is essentially an 'Optional Extra' and not part of the basic course.

The Greeks Had a Name

400 B.C.

If you are tempted to think that arguments about 'science and religion' are a new phenomenon, it is worth remembering that two and a half thousand years ago two Greeks, Democritus and Plato, fought the same battle. According to Plato the material

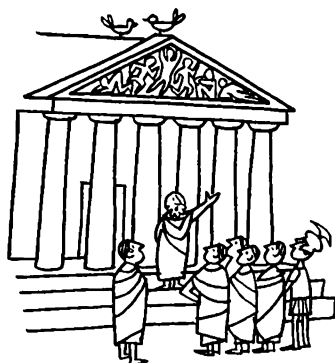


Fig. 519

world was 'unreal' and only the spirit 'existed'. He taught his followers to despise material things and to concentrate rather on the good and the beautiful. His opponent, Democritus, was one of the world's first 'materialist' philosophers. He taught that everything, including goodness and grief, could be interpreted in terms of the particles of matter. He is remembered today, however, more for his prophecy than his philosophy. Without any experimental evidence Democritus claimed that everything was made up of tiny hard particles which could not be seen although they had shape, size and weight. These particles he christened *atoma*, which means 'unsplittable' and from which we get our word *atom*. He said that they were continually in motion and that different substances were built up from different combinations of these atoms. More than 2000 years before the atomic age Democritus made this prophetic statement: 'The things which we perceive appear to be reality, but the atoms and empty space are the true reality'.

Aristotle, one of Plato's most brilliant pupils, also rejected the atomic theory of Democritus and accepted an idea of Empedocles that all substances are composed of four 'elements', earth, fire, air and water (Book 1, page 31). Aristotle did not, however, have Plato's contempt for matter. In fact, he studied matter so carefully, particularly plant and animal life, that for the next two thousand years he was accepted as the undisputed expert on all things scientific!



Fig. 520

Aristotle's false doctrine of matter encouraged a great many people to search for a way of mixing the 'elements' to produce gold. The alchemists (Fig. 520) were convinced that if they tried hard enough they would be able to change a cheap metal, such as iron, into gold. Many impostors claimed to have done this. In 1782, for example, James Price was honoured by the King and Oxford University for producing gold. When he was later forced to repeat his method of preparation before a learned audience he poisoned himself rather than admit his deceit.

Experimental Science Begins

1589 Aristotle's two thousand year reign came to an abrupt end when a young Italian scientist climbed to the top of the famous tower in Pisa. Whether this legend of Galileo is true or not, it is certain that he attempted to destroy the erroneous theories of Aristotle. It seems incredible to us that not everyone was immediately convinced by the evidence of his eyes, but so strong was the tradition that even in Oxford University anyone making an assertion against Aristotle was fined five shillings! Galileo not only laid the foundations of experimental science: he also supported the atomic theory, and thus cleared the way for those who followed to demonstrate experimentally the existence of the atom.



Fig. 521

1660 The search for the infinitely small took a new turn when a young Dutchman, Anthony van Leeuwenhoek, found a way of making and polishing a tiny spherical bead of glass which could be used as a high power microscope. He set the bead in a metal plate to which was attached his specimen (Fig. 521). With his microscope he was the first man to see bacteria, red blood corpuscles and tiny crystals of snow. He watched the circulation of the blood in the capillary vessels in a tadpole's tail, and calculated that there were millions of 'wee beasties' in a drop of water! His findings so astounded the Royal Society in London that they refused to believe him and sent a representative to Holland to see if this was a hoax. The result was his nomination as a member of the Royal Society!

Some of Leeuwenhoek's lenses had a magnifying power of $250\times$. With such a microscope he could study details down to about 1 micron, but this was still a long way from the atom!

You might like to try to make a simple bead microscope for yourself from a drop of water formed in a tiny loop of fine wire.

Chemistry Takes Shape

1661 A further attack on the alchemists came with the publication of Robert Boyle's book, 'The Sceptical Chymist'. In it Boyle introduced the idea of chemical *elements* as substances which cannot be split into other substances by chemical means. He suggested that all elements are made up of one kind of atom, and that different elements have different arrangements and movements of the atoms.

1700 By the beginning of the eighteenth century the atomic theory was becoming more popular. Newton argued that even light consisted of tiny particles or corpuscles. He demonstrated that white light could be split into 'spectral colours'. This was the beginning of modern spectroscopy, which yields important information about atomic and molecular structure.

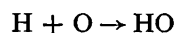
1738 The Swiss physicist Daniel Bernouilli explained the pressure exerted by a gas by suggesting that millions of minute particles, all in rapid motion, are continually colliding with the walls of their container and with each other. The kinetic theory of gases was born.

1802 Thomas Young produced optical interference patterns and thus demonstrated the wave nature of light.

1808 The first man to put the atomic theory on a firm experimental basis became a school-teacher at the age of twelve and a headmaster at nineteen! John Dalton claimed that every element had its own

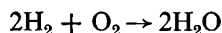
particular kind of atom. Such atoms were indivisible and indestructible, and all the atoms of a given element were identical. The atoms of different elements had different weights. Dalton's table of atomic weights produced a revolution in chemistry.

He was first to realise that in a chemical reaction elements combine in a fixed weight ratio because a certain number of atoms of one element always combine with a certain number of atoms of another. Dalton mistakenly assumed that the 'certain number' was in fact 'one' in each case. For example, he thought that one atom of hydrogen combined with one atom of oxygen to form water,



yet he knew that two volumes of hydrogen combined with one volume of oxygen to form two volumes of water vapour.

1811 The conflict was finally resolved by Gay-Lussac and Avogadro. Gay-Lussac discovered that, for a particular volume and pressure of gas, every gas expands by exactly the same amount when it is heated. Avogadro reckoned that this equal expansion must mean that the particles of all gases move apart by equal amounts when the gas is heated, and that therefore the average distance between the particles must be the same for all gases at the same temperature and pressure. This, in turn, implies that equal volumes of gases at the same temperature and pressure contain the same number of particles. In stating this hypothesis Avogadro named the gas particles *molecules*. By considering the molecule of a gas rather than the atoms, he was able to describe the combination of hydrogen and oxygen in an equation which agreed with experimental results



Since 2 volumes + 1 volume = 2 volumes

 2 molecules + 1 molecule = 2 molecules

i.e. $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$

Avogadro's hypothesis is also consistent with the kinetic theory of gases developed earlier (Book 3, page 159).

If the pressure p and the volume V of two gases are the same, then

$$pV = \frac{1}{3}n_1m_1\overline{v_1^2} = \frac{1}{3}n_2m_2\overline{v_2^2} \quad . \quad (1)$$

and if they are also at the same temperature then

$$\frac{1}{2}m_1\overline{v_1^2} = \frac{1}{2}m_2\overline{v_2^2} \quad . \quad . \quad . \quad . \quad (2)$$

From these two equations we see that

$$n_1 = n_2;$$

that is, the number of molecules is the same in equal volumes of gas at the same temperature and pressure.

1812 In the gradual development of the present picture of the atom, emission and absorption spectra have played an important part. Joseph von Fraunhofer, a German physicist and expert lens maker, was first to report a series of some 576 dark lines across the spectrum of the sun. He found that the same lines appeared in light

from the moon and the planets, but that the spectra of starlight contained *different* lines. From this he concluded that the lines must originate in the source of light. About fifty years later Kirchhoff and Bunsen demonstrated that each element had an emission spectrum which contained a unique set of lines.

- 1827 The first experimental evidence of molecules in motion was produced by someone who was never to realise the implications of his discovery. The botanist Robert Brown had mixed a little pollen in a drop of water and was studying it under his microscope. To his amazement the pollen grains danced around in a completely random way without stopping or even slowing down. He was unable to explain this movement and said that the pollen grains behaved like tiny insects. It was not until nearly a hundred years later that the French physicist Jean Perrin made careful measurements of a suspension of gamboge and showed that the particles were constantly colliding with water molecules.

- 1834 The idea that a small but definite electric charge might be associated with each different atom was suggested by Michael Faraday. He discovered that when a definite quantity of electricity passed through a solution, the masses of the substances liberated at the electrodes were proportional to their equivalent weights

i.e. to
$$\frac{\text{atomic weight}}{\text{number of valence electrons}}.$$

- 1869 Certain elements have such similar chemical and physical properties that they are often thought of as forming a 'family'. The halogens, inert gases and alkali metals are striking examples. The Russian chemist Dmitri Mendeleev first showed that, if all the elements are listed in order of their atomic weights, elements with similar properties recur at regular intervals. There were one or two odd exceptions, which Moseley explained forty years later.

- 1885 The Swiss schoolmaster, J. J. Balmer, found that the wavelength of all the lines in the visible part of the hydrogen spectrum could be described by a single mathematical formula.

Rays, Radium, Rutherford

- 1895 Wilhelm Röntgen discovered the amazing properties of X-rays.

- 1896 In the following year Becquerel tried to produce X-rays from fluorescent material and discovered that uranium salts emit radiations which affect photographic film and discharge electroscopes even in total darkness. Radioactivity had been discovered—the unsplitable was splitting!

- 1897 In the Cavendish laboratory at Cambridge, J. J. Thomson (Fig. 522) 'discovered' the electron; that is, he measured the charge/mass ratio for cathode rays and showed that they were composed of negatively charged particles much smaller than the lightest atom. For his contributions to atomic physics Thomson was awarded the Nobel Prize in Physics in 1906.

Thomson later proposed a model of the atom sometimes called the 'plum pudding model', as it pictured the atom as a positively charged material with negative electrons stuck in it like plums in a pudding.



Fig. 522

1898



Fig. 523

The search for and the eventual discovery of the most drab and yet the most dramatic element in the periodic table. Maria Skłodowska had won a gold medal for her work in physics. Unfortunately her father could not afford to send her to university to study mathematics. But this did not deter Maria. She went to a rich Polish family, and after she had saved enough money to go to Paris, she met one of Becquerel's colleagues. Here her cooperation was not limited to the search for radioactivity. She became Madame Curie. After her husband's death she decided to study Becquerel's mysterious phenomenon. She started by investigating whether any other elements emitted these strange rays that thorium did. She christened the phenomenon radioactivity.

Continuing her investigations, Madame Curie found some minerals containing thorium which were more radioactive than she would have expected. She discovered yet another substance that was more radioactive than either uranium or thorium.

Pierre decided to give up his own work and join the search for this strange new substance. They decided to find large enough quantities of material at a price they could afford. Fortunately uranium had been extracted from the waste of glass, the waste was just as radioactive. The waste material they could have for a long, tedious task of chemical analysis.

The laboratory was an old rickety shed. Madame Curie spent nearly four years of unbroken work, evaporating and filtering. She wrote to her mother with some concoction or other, stirring the pot as myself. By the evening I was worn out.

'We spent the best and happiest years of our lives entirely devoted to the task in that miserable old shed'.

After refining tons of pitchblende, Madame Curie produced a few crystals of two new elements. The first she named after her native Poland—*polonium*, the other was named *radium*, from the Latin word meaning 'to radiate'.

Thanks to the inexhaustible patience and tireless efforts of Madame Curie and her husband, the mountain of waste had yielded a tenth of a gramme of radium! This amazing element is two million times more radioactive than uranium. Since its discovery, its radiations have been used in thousands of ways, including the treatment of cancer. Its rays are also very dangerous, and Madame Curie's death at the age of 67 is now known to have been due to leukemia, a disease thought to be caused by gamma radiation.

1900 About the turn of the century radioactivity was found to consist of three distinct types of radiation. Ernest Rutherford named two of them alpha and beta rays, and Paul Villard discovered the third—gamma rays. The Curies showed that beta rays carry a negative charge.

1903 Rutherford and Robinson then deflected alpha rays with powerful electric and magnetic fields and showed that they carried positive charges. They were then able to measure the charge/mass ratio, which showed that alpha rays consisted of positively charged particles each with about 7000 times the mass of an electron.

Later, Rutherford and Royds showed that an alpha particle was in fact identical with the nucleus of a helium atom.

About the same time, the German physicist Philipp Lenard was first to show experimentally that the atom had an open structure. He made a cathode ray tube with a small aluminium window in it and found that fast-moving electrons could go straight through this 'Lenard window'. He asserted that the atom was just empty space apart from about one part in a thousand million. For his work on cathode rays he received the Nobel Prize in 1905.

1905 Einstein then startled the world by putting forward the theory that matter (mass) and energy are equivalent. These he related by his famous equation

$$E = mc^2$$

joules kilogrammes

If a lump of sugar could be changed to energy it would provide enough heat to keep a room warm for thousands of years!

1910 After investigating radioactive decay and atomic structure, the English chemist Frederick Soddy concluded that substances with *identical* chemical properties could have different atomic weights. As these substances must be forms of the same element and must therefore appear in the 'same place' in the periodic table, he proposed they be called *isotopes*. All isotopes of an element have the

same atomic or proton number but different mass or nucleon numbers. Soddy was awarded the Nobel Prize in 1921.

The development of the mass spectrograph in 1919 by F. W. Aston enabled him to separate and identify the different isotopes of an element.

The Scattering Experiment

Ernest Rutherford was not happy about Thomson's plum pudding model of the atom and suggested to his colleague Geiger that he might like to give one of his students, Ernest Marsden, a small research project. "Why not let him see if any alpha particles can be scattered through a large angle?" Rutherford asked, although he admitted later that he did not expect a positive result!

Geiger and Marsden's experiment is illustrated in Figs. 524 and 525. A radium source is placed inside a lead box so that it emits a narrow beam of alpha particles, which produce tiny flashes of light when they strike a zinc sulphide screen. Without the gold leaf in position the flashes were observed through a microscope focused on screen 1 (Fig. 524). Even the thinnest gold foil, less than a micron, is still several hundred atoms thick. When such a foil was placed in the path of the alpha particles it made practically no difference. They shot through this wall of gold as if it wasn't there! If Thomson's model of the atom was correct, this was like firing a continuous stream of bullets through a mountain! But even more exciting results were to follow.

The zinc sulphide screen could be rotated to other positions (for example, positions 2, 3 and 4 in Fig. 524) so that any alpha particle deflected from its original course could be detected. Geiger then reported to Rutherford that they had detected some of the alpha particles 'coming backwards'. Later, Rutherford said "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15 inch shell at a piece of tissue paper and it came back and hit you!"

As a result of Geiger and Marsden's experiments, Rutherford proposed a new model of the atom. He thought of it as a solid core or nucleus surrounded by distant electrons. The mass of the atom was concentrated at the core, a fact which explained the deflection of the very occasional alpha particle (Fig. 525). In all only about 1 in every 8000 particles was deflected more than 90° .

Fig. 526 illustrates a magnetic model of the scattering process. In it, tiny ring magnets represent the nuclei of the atoms and the alpha particles are similar magnets floating on carbon dioxide. The photograph was taken by a series of time exposures, each showing the path of a magnet fired from the left-hand side of the photograph.

Not only did Geiger and Marsden's experiment provide evidence for the *nuclear atom*, but it also enabled the size of the nucleus and the charge it carried to be measured. The nuclear charge was found always to be a multiple of the electronic charge, the value of which Millikan had so carefully measured, and the diameter of the nucleus was calculated as one ten-thousandth part of the diameter of the atom! As the mass of the atom is concentrated in this tiny nucleus, you can imagine what might happen if all the 'electronic space' were to disappear and a concentrated lump of

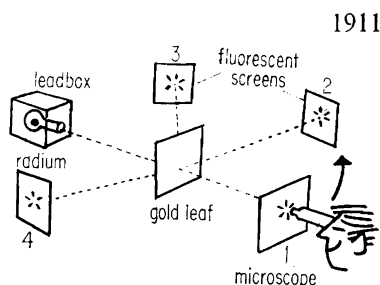


Fig. 524

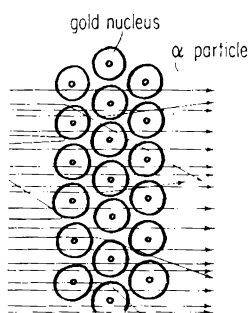


Fig. 525

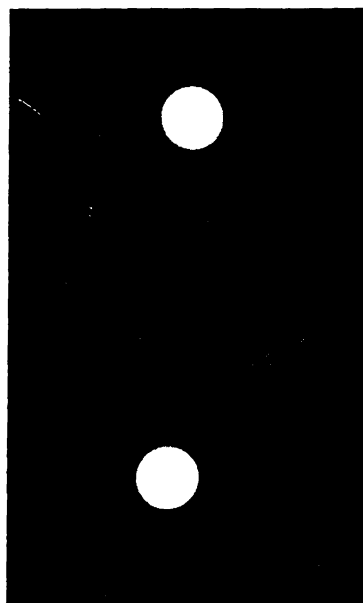


Fig. 526

nuclei were available. Fortunately such a thing is impossible on the earth, but astronomers tell us that in the white dwarf stars the nuclei are so closely packed that a spoonful of matter from one of these stars would weigh hundreds of tons!

You have seen evidence for the nuclear atom in the alpha particle tracks found in a cloud chamber, which was invented by C. T. R. Wilson in 1911. Each track, a few centimetres long, is formed from hundreds of thousands of ions. The alpha particle must have travelled through that number of atoms without ever striking a nucleus. Only very occasionally does an alpha particle strike a nucleus and produce a forked track. Fig. 539 shows such a collision, where an alpha particle has been in collision with a nitrogen nucleus.

Atomic Models

1913 The next Nobel Prize winner in our story is Niels Bohr, of Copenhagen. He came to England in 1911 and started work in Cambridge under J. J. Thomson. Soon he moved to Manchester to work with Rutherford on the structure of the atom.

Rutherford had described the atom as a small positively charged nucleus with electrons circling round it rather like planets in a miniature solar system. A circling electron is, however, accelerating all the time, so it ought to radiate electromagnetic waves. Yet there is no evidence to suggest that any such radiation exists or that an atom is continuously losing energy. Bohr set his mind to the problem.

He knew that atoms *did* emit electromagnetic radiation if they had been excited by collisions with other atoms, and that the frequencies of the waves emitted were different for different elements. The work of Planck (1901) and Einstein (1905) had shown that the energy changes associated with radiation could be interpreted as definite *quanta* or bursts of energy which are proportional to the frequency of the radiation.

Bohr produced a model of the atom in which electrons can move, without radiating, only in *certain* orbits or shells. If an electron jumps from one particular orbit to one nearer the nucleus, that is, from a high energy level to a lower energy level, energy is radiated as electromagnetic waves. The frequency of the radiation is then dependent on the difference between the two energy levels (Fig. 527).

This model was an improvement on Rutherford's model and, following the work of Balmer and other spectroscopists, led to more satisfactory explanations of optical and X-ray spectra, as we shall see.

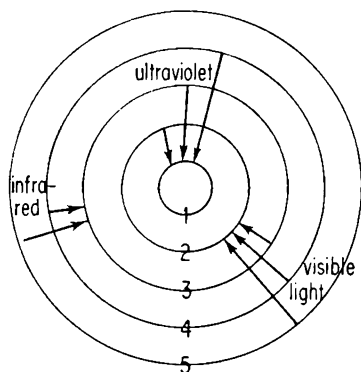


Fig. 527

Particles or Waves?

Fig. 528 shows a diffraction pattern produced on the end of an electron tube₁ (Tel 555). The fact that a stream of electrons can produce such diffraction effects strongly suggests that electrons behave like waves. The results of electron diffraction experiments first led Louis de Broglie to propose the wave nature of the electron.

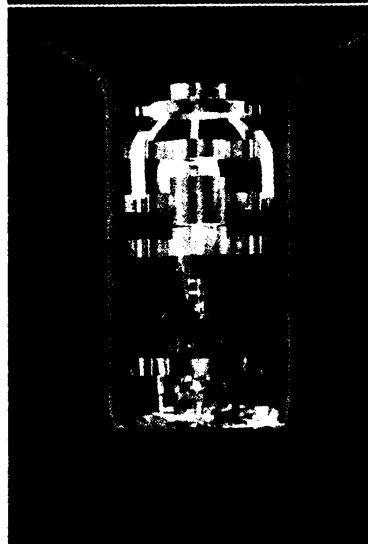
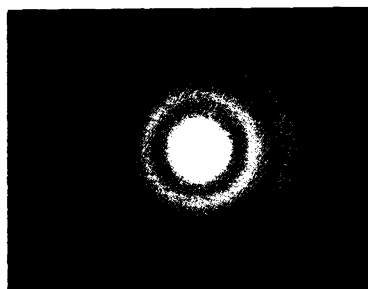


Fig. 528



Fig. 529

The idea was later developed mathematically by Schrödinger in his *wave mechanics*.

(An optical analogue of electron diffraction is available commercially.)

Experiment 13.1

(i) If a long spiral spring_{2.4} is supported by a large number of threads (Fig. 529) standing waves can be set up in it. Try this, and notice that such waves are possible only at certain frequencies. Each of these corresponds to an integral number of complete waves in the spring.

(ii) An alternative experiment is shown in Fig. 530. In it a long fine coil spring is made to vibrate on an Advance vibrator. Vary the frequency, and see when standing waves are produced.

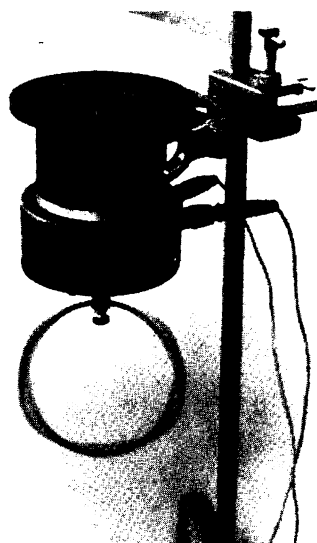


Fig. 530

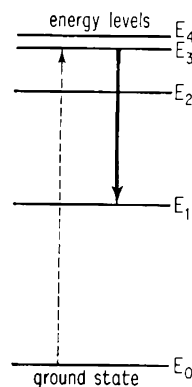


Fig. 531

The above experiments show that only certain patterns are stable.

If we consider the electron as having wave properties, including *wavelength*, we can postulate that an electron can circle the nucleus indefinitely without radiating energy, provided the circumference of its orbit is an integral number of *electron wavelengths*. Each of these orbits corresponds to a definite energy level.

If an electron jumps from one energy level (E_3) to a lower level (E_1), a quantum of energy will be radiated (Fig. 531). The frequency of the radiated photon will be proportional to the difference in energy between these two levels. The constant of proportionality (h) is called Planck's constant.

$$E_3 - E_1 = hf$$

From Fig. 527 we see that this particular frequency is in the ultraviolet spectrum.

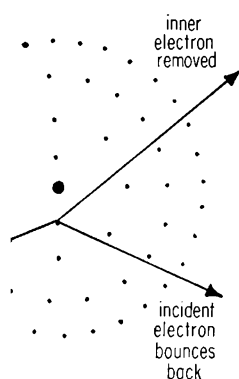


Fig. 532

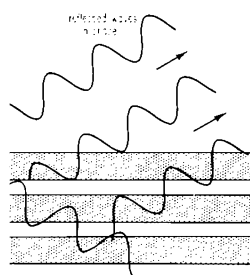


Fig. 533

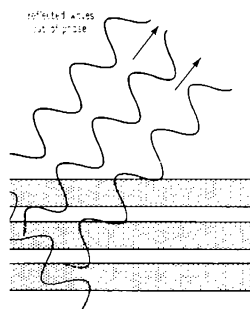


Fig. 534

Atomic (Proton) Number

Characteristic X-rays are known to be produced when electrons jump from one energy level to another. When high speed electrons bombard a target, an inner electron in one of the target atoms may be removed (Fig. 532). An electron at a higher energy level then jumps in to the vacancy, and in so doing emits X-rays. The frequencies of the X-rays produced are characteristic of the target material used.

At first there was great speculation about the nature of X-rays. Since optical diffraction gratings would not bend them, they appeared to have a much smaller wavelength than light, if in fact they were waves at all. Then in 1912 the German physicist Max von Laue suggested that the regular layers of atoms in a crystal might be used as a natural diffraction grating. If X-rays are partially reflected from each of these layers, which are about 1 micron apart, the reflected waves would be in phase (Fig. 533) or out of phase (Fig. 534), depending on the angle of incidence of the beams. Using this technique Laue's assistants were able to show that X-rays were indeed very short electromagnetic waves. If a narrow beam of X-rays is reflected from a rotating crystal, a line spectrum characteristic of the particular crystal can be obtained (Fig. 535).

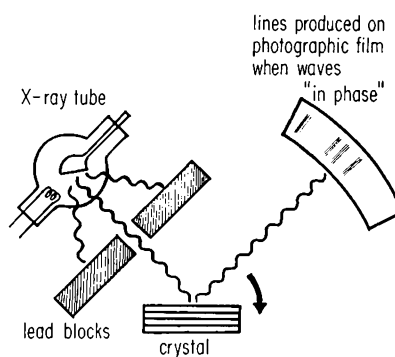


Fig. 535

One of Rutherford's associates at Manchester was a young man who was fascinated by these X-ray spectra. His name was Henry Moseley. He decided to investigate the X-ray spectra of as many elements as possible. To do this he had to build a very unusual X-ray tube. It consisted of a long wide glass tube containing a toy railway line on which a truck carried a number of different elements. Moseley used these elements in turn as targets into which he fired electrons in order to produce X-rays. In other words the elements formed the *anode* of the X-ray tube.

In addition to being a very skilful experimenter, Moseley had the same kind of devotion and enthusiasm as we have seen in Madame Curie. He could be seen at work day and night, and it was said of him that one of his specialised attainments was knowing where to get a meal in Manchester at three o'clock in the morning!

Moseley very quickly produced results which, Rutherford claimed, rank in importance with the discovery of the periodic table and spectral analysis. He found that the *frequency* of a

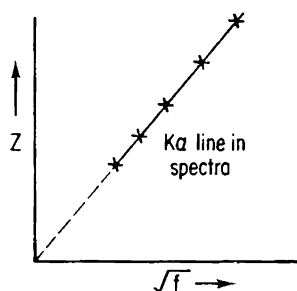


Fig. 536



Fig. 537

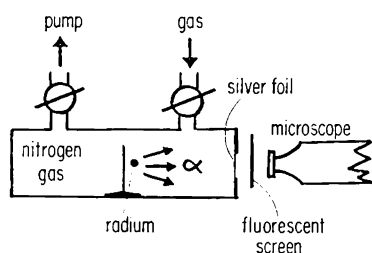


Fig. 538

particular line in the X-ray spectrum of an element increased regularly from element to element. The order he obtained was very similar to the order of elements in the periodic table but much better! The strange discrepancies had disappeared. Arranged in order of atomic weights potassium came before argon, and nickel before cobalt. With Moseley's arrangement these orders were reversed, and the elements then fell into the correct vertical columns with elements of similar chemical properties (see end paper). Moseley said of his results, 'We have here a proof that there is in the atom a fundamental quantity which increases by regular steps as we pass from one element to the next. This quantity can only be the charge on the central positive nucleus'. It is now called the atomic number or proton number (Z). Chadwick later confirmed this conclusion by scattering alpha particles from various metals.

It is the *atomic number* then and not the *atomic weight* that determines the chemistry of an element.

When the square root of the frequency is plotted against the proton number (Z), a straight line is obtained (Fig. 536). Using this graph it was possible to 'call the roll' of the elements, and several 'absences' were discovered. The missing elements have now all been found.

Moseley's amazing work was done when he was only 26 years old. Two years later he was killed by a sniper's bullet while serving as an army officer in the Dardanelles. His unnecessary death was a major disaster for science throughout the world.

Clear experimental evidence for the existence of distinct energy states within the atom was produced by the German physicists Franck and Hertz. They bombarded vaporized sodium with electrons from a heated filament. This experiment also won a Nobel Prize.

All Change

One of Ernest Rutherford's ambitions was to be the world's first successful alchemist! He argued that, if an element's chemistry depends on the number of charges in its nucleus, it should be possible to change both by bombardment.

Fig. 537 shows Rutherford holding the simple apparatus which he designed to try out his theory. It is shown diagrammatically in Fig. 538. The small chamber was evacuated and filled with nitrogen gas. Alpha particles from the radium source were then fired at a small silver foil which was sufficiently thick to stop them. Any scintillations on the fluorescent screen beyond the foil could be observed through a microscope. When Rutherford peered through the microscope he saw nothing at first and then suddenly a tiny twinkle of light appeared . . . and then another. From measurements with applied magnetic and electric fields Rutherford identified the responsible particles as hydrogen nuclei (protons).

Rutherford's student, P. M. S. Blackett, in a series of 23,000 cloud chamber photographs showing some 400,000 alpha particle tracks, found only eight photographs of the transmutation. Fig. 539 is one of them. By assuming that momentum was conserved in this collision, the other particle formed was identified as an

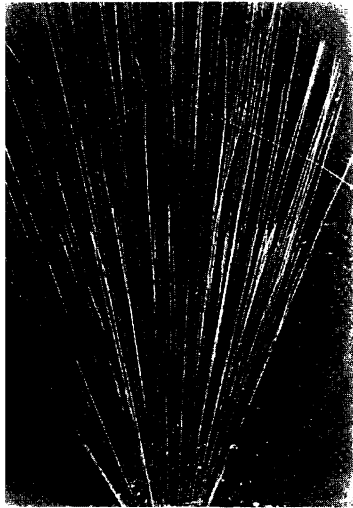


Fig. 539

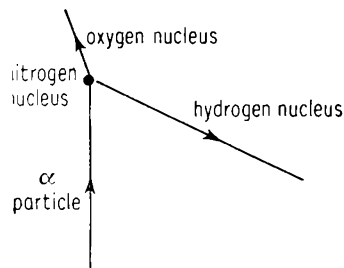


Fig. 540

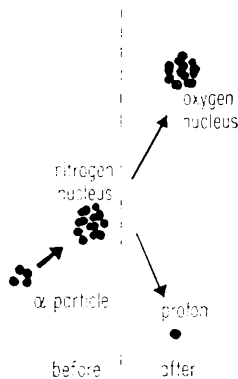
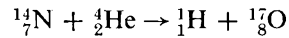


Fig. 541

oxygen nucleus. So nitrogen had been changed to hydrogen and oxygen by bombardment with an alpha particle. For the first time in man's history the atom had been split and one element changed to another.

The collision may therefore be represented by Fig. 541 or by the equation



By measuring the lengths of the two tracks it was possible to calculate the kinetic energy of each particle. It was then discovered that about 1.26 MeV (2×10^{-13} joules) of energy had been lost in the collision.

Here are the masses on both sides of the equation.

$${}^4_2\text{He} = 6.64632 \times 10^{-27} \text{ kg} \quad {}^1_1\text{H} = 1.67350 \times 10^{-27} \text{ kg}$$

$${}^{14}_7\text{N} = 2.32521 \times 10^{-26} \text{ kg} \quad {}^{17}_8\text{O} = 2.82271 \times 10^{-26} \text{ kg}$$

Find the gain in mass as a result of this collision. (2)

Calculations of this kind gave the first experimental evidence of Einstein's prediction that mass and energy are equivalent. *Use the above figures to verify the relationship $E = mc^2$ (3).*

Although in this particular collision energy has been changed to mass, in many other atomic collisions the total mass is reduced and the particles leave with much greater energy. A nuclear explosion is an example of mass 'changing to energy'. Nowadays particle accelerators such as the synchrotron are used to smash atoms. Fig. 542 shows part of the 7 GeV proton synchrotron Nimrod (Genesis 10.8) at the Rutherford High Energy Laboratory.

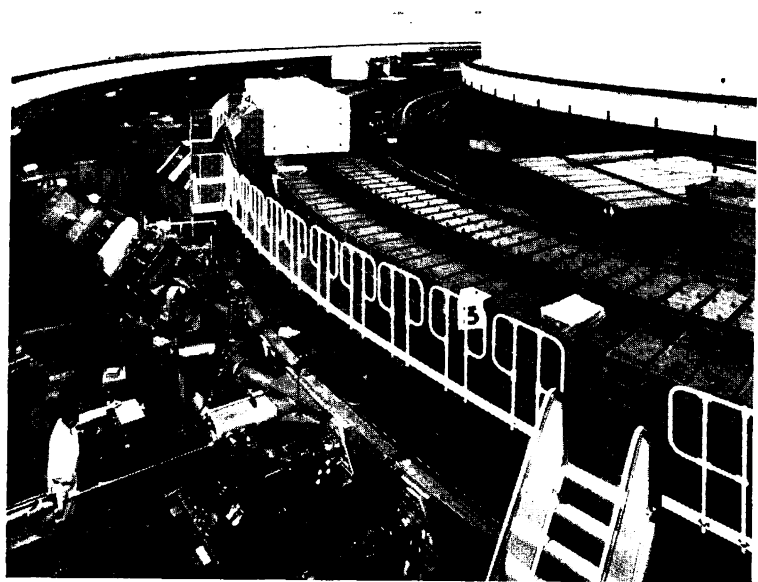


Fig. 542

1928

Geiger and Muller in Germany developed a new kind of tube for counting radioactive disintegrations. This is the type normally used now with a scaler or ratemeter.

1931 Van de Graaff made his first electrostatic generator which could produce voltages of over a million volts. Fig. 543 shows a modern version of this generator.

1932 James Chadwick discovered the neutron and Carl Anderson discovered the positron.

1932 Working at Cambridge, Cockcroft and Walton designed and built the first 'atom smasher' or particle accelerator. With it they



Fig. 543

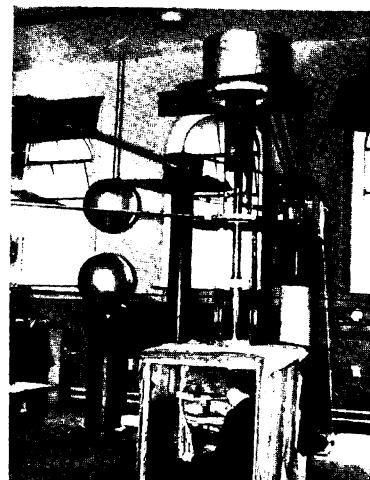


Fig. 544



Fig. 545

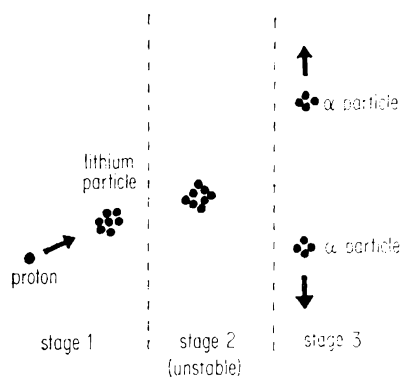
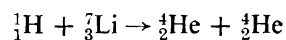


Fig. 546

hoped to produce nuclear transmutations with artificially accelerated protons. A voltage multiplying device, consisting of a step-up transformer feeding several rectifiers and capacitors, produced about half a million volts. This was applied to a long vertical tube made from glass cylinders taken from old petrol pumps. The cylinders were fastened together with metal plates and plasticine! (Fig. 544.)

Protons, produced in a discharge tube in the upper vessel, were accelerated down the tube by the strong electric field until they reached about 10,000 kilometres per second. They then struck a lithium plate and occasionally a few scored direct hits on lithium nuclei. Rutherford's well-tryed zinc sulphate screen was used to detect any particles emitted. It was soon clear that alpha particles were being shot off the lithium target in pairs. Later experiments using a cloud chamber (Fig. 545) confirmed that, when a proton struck a lithium nucleus, two alpha particles travelling in opposite directions were formed.

This, the first atomic disintegration produced by artificially accelerating particles, may be represented by Fig. 546 or by the following equation



When the cloud chamber tracks were measured, it was clear that the energy of the alpha particles was *very* much greater than the energy of the proton.

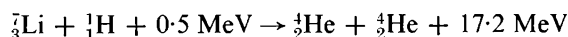
Energy in atomic physics is measured in *electron-volts*. When an electron or proton is accelerated by a difference of potential of 1 volt the *energy* gained is 1 electron volt (eV).

$$1 \text{ electron volt} = 1.6 \times 10^{-19} \text{ joules}$$

When a proton in Cockcroft and Walton's generator was accelerated by a potential difference of 500,000 volts, its final kinetic energy was therefore 500,000 electron volts or 0.5 MeV.

The two alpha particles were each found to have energies of about 8.6 MeV, a total of 17.2 MeV. This may seem a very small amount of energy, a few millionths of a millionth of a joule; nevertheless this energy released by splitting the lithium atom is many *millions* of times greater than the energy released by (say) a carbon atom when coal is burned.

The above nuclear reaction could therefore be more correctly written as



Mass values for each side of the equation are given below.

$${}^6_3\text{Li} = 1.16500 \times 10^{-26} \text{ kg} \quad {}^4_2\text{He} = 6.64632 \times 10^{-27} \text{ kg}$$

$${}^1_1\text{H} = 1.67350 \times 10^{-27} \text{ kg}$$

Use $E = mc^2$ to see if the sum of the mass + energy is the same on both sides of the equation. (4)

Fig. 547 shows a modern version of the Cockcroft-Walton high voltage generator.

Later in 1932, E. O. Lawrence in America used his Nobel-Prize-winning cyclotron to split atoms of lithium.

Softly Softly Catchee Monkee

1934

The Juliot-Curies discovered artificial radioactivity. They used alpha particles to bombard some light elements which then became radioactive. In the same year Lawrence in America and Fermi in Italy produced radionuclides artificially by bombarding stable elements with accelerated particles.

Fermi discovered that *slow moving* neutrons were particularly effective. During one experiment the neutron source and target were placed on a wooden table, and the rate of disintegration of the target atoms mysteriously increased! Fermi solved the puzzle and was awarded a Nobel Prize.

Some of the neutrons must have collided with the hydrogen atoms in the wood. They had then been deflected and *slowed down*. The slower neutrons were more easily captured by the nuclei of the target atoms, and so more radioactive nuclei were formed and the rate of disintegration increased.

When one particle collides elastically with another, the speed of the original particle will be altered *most* if the second particle has the same mass. In a head-on collision of this kind with a stationary particle, the original particle will be stopped. (Cf. strobe photo in Book 3, page 81.) In other collisions between particles of equal mass, the speed of the first particle will be reduced (cf. Book 3, pages 84 and 113).



Fig. 547



Fig. 548

If the second particle has a much larger mass, the first will be deflected but its speed will not be greatly altered (cf. Book 3, page 112, Fig. 192 in which the second puck has, in effect, a very large mass, as it is part of the Earth to which it is firmly fixed).

Ideally then a neutron should be made to collide with another neutron, proton or hydrogen atom in order to reduce its speed. This is not always possible, as we will see later, but a number of collisions with any of the *lighter* atoms will greatly reduce the speed of the neutron.

The chances of a *slow* neutron being captured by a nucleus are greater because it spends a larger time in the vicinity of the nucleus. The following analogies must not be taken too seriously, but they may help to illustrate the point. A magnetic dry ice puck fired at a stationary fixed puck of opposite polarity can be made to *pass by* if it is travelling quickly. If, however, it is moving slowly past, the two will be attracted to each other and coalesce. Alternatively, think of a golfer striking the ball too hard, so that it doesn't drop into the hole even though the aim is perfect! (Fig. 548.)

The normal random movement of molecules (heat) is sometimes called *thermal motion*. As slow neutrons are moving at speeds similar to those of molecules at room temperature, they are often called *thermal neutrons*. Fermi used such neutrons to bombard various substances, including uranium. From this he obtained new radionuclides which he could not identify. He thought he had produced elements with atomic numbers greater than uranium—the so-called *transuranic elements*.

In Germany Frau Ida Noddack suggested that, when heavy nuclei are bombarded with neutrons, they might break up into a number of large pieces which would be isotopes of other elements! This idea was, however, considered by all the physicists of the day to be completely absurd. During the next few years many other physicists repeated Fermi's work but failed to explain the results obtained.

Nuclear Fission

1938 Four years after Fermi's original experiment, the German scientists Otto Hahn and Fritz Strassmann were forced to admit that when they subjected the uranium 'radionuclides' to careful micro-chemical analysis they found *barium*. Yet they could hardly believe this was possible! Uranium has 92 protons and barium 56 in its nucleus. Never before had a nuclear change of this magnitude been observed.

Fraulein Lise Meitner and Otto Frisch, two refugees from Hitler's Reich, were in Denmark at the time. They reckoned that, if Hahn and Strassmann's results were correct, krypton should also be present as it has 36 protons in its nucleus



Further experiments confirmed this prediction. The uranium nucleus had in fact split into two parts. The process was labelled fission, a name borrowed from the biologist's description of cell division. Its announcement led to a flurry of excitement and about a hundred papers on nuclear fission were published in 1939.

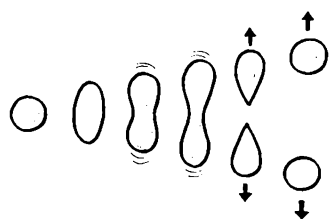


Fig. 549

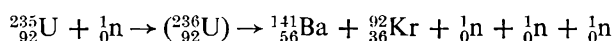
Niels Bohr and John Wheeler suggested a model in which the nucleus is compared to the oscillations of a water drop. If the amplitude of oscillations is large enough the drop will break up (Fig. 549). In the nuclear case the necessary energy for fission is provided by the captured neutron.

Fission of the uranium nucleus was certainly interesting, but much more exciting results were to follow. Meitner had calculated that a large amount of energy was released when the uranium nucleus split. In 1939 Fermi's associates working with a cyclotron at Columbia University were able to measure the amount of ionisation produced by the fission fragments, and from this they found the energy released. It was about 200 MeV for each fission. If 1 gramme of uranium-235 were used each day it could produce energy at a continuous rate of 1 megawatt.

1939

This was not all. Fermi suggested and later confirmed experimentally that when the uranium nucleus split neutrons were released. These in turn might produce further fissions. A chain reaction was possible. The implications were shattering.

The most useful uranium isotope to produce nuclear fission is uranium-235. When it is bombarded by neutrons, the nuclear reaction may be represented by the equation



The unstable nuclide uranium-236 which is formed immediately splits up into barium-141, krypton-92 and two or three neutrons.

Unfortunately natural uranium contains only 0.7 per cent of uranium-235, while more than 99 per cent is uranium-238 which absorbs neutrons but is not fissionable. It was found, however, that *slow* neutrons usually bounced off the uranium-238 nuclei and were captured by the uranium-235 nuclei to produce fission.

1942

The most suitable light element to slow down neutrons was graphite. Others had been tried but they absorbed too many of the neutrons. Pure graphite slowed the neutrons down but did not absorb them.

By 1942 World War II was in its third year and most of the world's leading physicists were in America. One group led by Enrico Fermi were working night and day in a squash court under the grandstand of a football stadium in Chicago. They were building the world's first nuclear reactor or 'atomic pile' as it was then called.

In a nuclear reactor the object is to adjust the reaction so that, on the average, one neutron per fission will split another nucleus. The operation is outlined in Fig. 551. A slow neutron is first captured by a uranium-235 nucleus, which then splits to form two nuclides which fly apart at speed. Three fast neutrons are also emitted. These then pass through a graphite *moderator*, in which they collide many times with the carbon atoms and are thus slowed down. One may escape completely, another may be captured by a uranium-235 nucleus which splits and a third, which may not have been slowed down quite so much, is absorbed by a uranium-238 nucleus which changes to plutonium. If the three new neutrons behave similarly, a sustained nuclear reaction will result and heat will be produced at a steady rate.

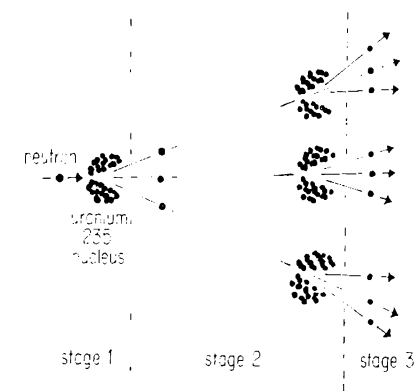


Fig. 550

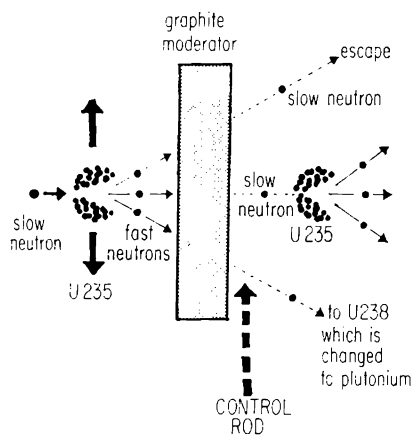


Fig. 551

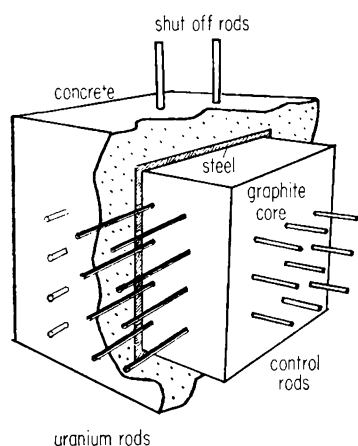


Fig. 552

To slow down or stop the reactor, *control rods* made of cadmium, which readily absorbs neutrons, are inserted.

Fermi's squash court reactor was made from a pile of uranium and graphite blocks. It was about 8 metres high. Fig. 552 shows a later form of reactor based on the same principle. The uranium fuel rods are kept in aluminium tubes and the cadmium rods are pushed into the reactor to slow it down. Reactors are now encased in a wall of concrete about 2 metres thick to prevent the escape of gamma radiation. This is called a biological shield.

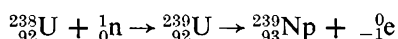
At 3.30 p.m. on December 2, 1942, Fermi's pile produced the first nuclear chain-reaction. Later the same day the following telephone conversation took place between Chicago and Harvard University.

'The Italian sailor has landed in the New World'.

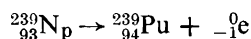
'How were the natives'?

'Very friendly . . .'

The atomic age had begun.



In his reactor Fermi produced plutonium from the uranium-238. When bombarded by moderately slow neutrons a uranium-238 nucleus can capture one and become an unstable nuclide which decays ($t_{\frac{1}{2}} = 24$ min) by the emission of a beta particle to form the first transuranic element, *neptunium*.



Neptunium in turn decays ($t_{\frac{1}{2}} = 2.3$ days) by beta emission to form plutonium, which is one of the most valuable radionuclides today. It has a half life of 24,300 years! Like uranium it will fission with slow neutrons and is likely to be a most important fuel for nuclear power stations in the future.

Eleven transuranic elements have now been produced. They are 93-neptunium, 94-plutonium, 95-amerium, 96-curiun, 97-berkelium, 98-californium, 99-einsteinium, 100-fermium, 101-mendelevium, 102-nobelium, 103-lawrencium.

The Atom Bomb

Another group of atomic physicists led by Robert Oppenheimer was furiously trying to produce the first atom bomb. For this pure uranium-235 was needed, yet natural uranium contains only 0.7 per cent of this nuclide. As U-235 and U-238 are chemically identical, they could not be separated chemically. Another way had to be found. A sieve from his wife's kitchen gave Professor Simon an idea! If natural uranium was vapourized and allowed to pass through a very fine sieve, the lighter uranium-235 atoms could pass through faster than the heavier atoms, and the percentage of U-235 to U-238 would be greater beyond the sieve. This diffusion process had to be repeated thousands of times in order to obtain reasonably pure uranium-235. The mammoth task—the Manhattan Project—was undertaken at Oak Ridge, Tennessee. The plant (Fig. 553) and 'artificial town' round it covered 70 square miles and employed about 80,000 people. Even so, the output was only a few kilogrammes of uranium-235 per week.

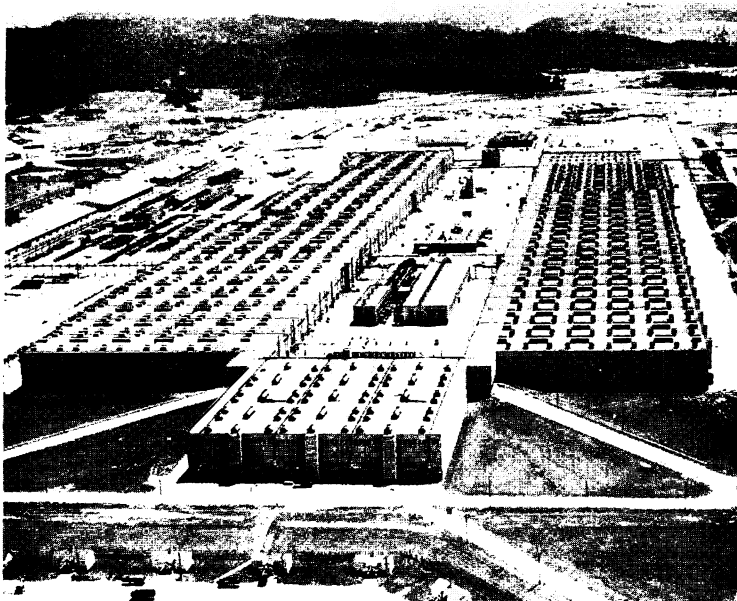


Fig. 553

With U-235 no moderator is needed to slow down the neutrons, as the nucleus will readily accept fast neutrons. Chain reaction will not, however, take place in small chunks of U-235, as most of the neutrons produced escape through the surface.

Consider a sphere of U-235 with a radius of 2 centimetres. The surface area is $4\pi r^2$, that is, $4\pi \times 4$ and the volume $\frac{4}{3}\pi r^3 = \frac{4}{3}\pi \times 8$. The ratio of area/volume is therefore

$$\frac{4\pi 4}{\frac{4}{3}\pi 8} = \frac{3}{2} = 1.5$$

If the radius is doubled, the ratio becomes

$$\frac{4\pi 16}{\frac{4}{3}\pi 64} = \frac{3}{4} = 0.75$$

As the volume and hence the *mass* of uranium is increased, the surface area per unit volume becomes less and less, and so the chance of neutrons escaping becomes less and less. By increasing the mass, then, the chance of each new neutron producing a fission is increased, until eventually a point is reached when a chain reaction is possible. The mass of U-235 needed for this to happen is called the *critical mass*.

The principle of the atom bomb is shown in Fig. 554. Two hemispheres of U-235 well below the critical mass are kept apart inside a strong metal container. To explode the bomb one piece is violently forced against the other by a conventional explosive. The total mass is then greater than the critical mass.

There are always a number of neutrons flying around. Several hundreds are estimated to pass through our bodies every second,

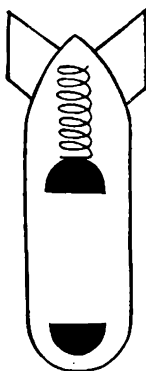


Fig. 554

many of them produced by cosmic radiation. Thus, as soon as the mass of U-235 in the bomb exceeds the critical mass, a violent explosion takes place.

On July 16, 1945, the world's first atom bomb was exploded in a remote desert plateau in New Mexico. A small piece of uranium, smaller than a football, had changed the history of the world.

Nuclear Power

1951 After the war atomic piles were rapidly developed to produce energy for peaceful purposes. The heat produced in the reactor had to be made available to power a steam turbine, which could then drive a dynamo to produce electricity. This was first accomplished in 1951, although it was five years later before the world's first nuclear power station was opened at Calder Hall in Cumberland (Fig. 555).

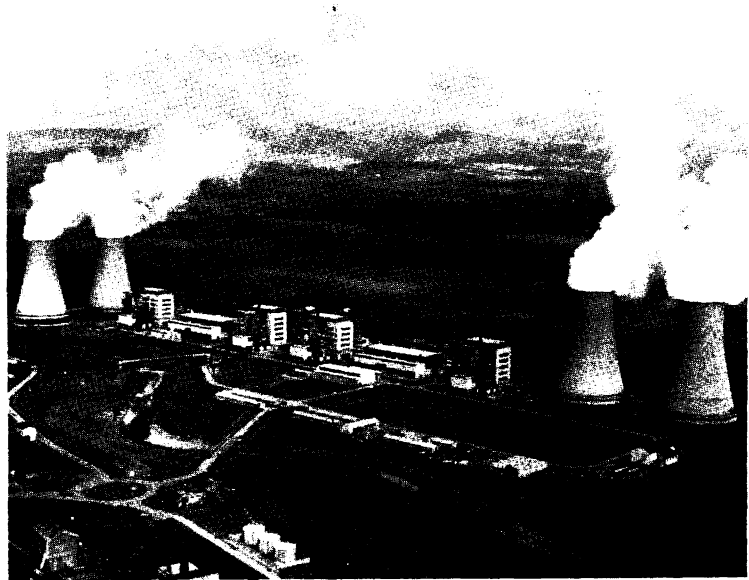


Fig. 555

Most modern reactors operate on the principle indicated in Fig. 556. Uranium fuel rods are encased in graphite blocks and cadmium rods control the reaction. The reactor is contained in a strong *pressure vessel* through which a gas or liquid metal flows in order to transfer the heat from the reactor to a steam boiler. Thereafter a nuclear power station is no different from an oil or coal burning one. Nuclear fuel simply replaces the fossil fuels used in a conventional station.

Since 1959 an experimental fast reactor has been in use in

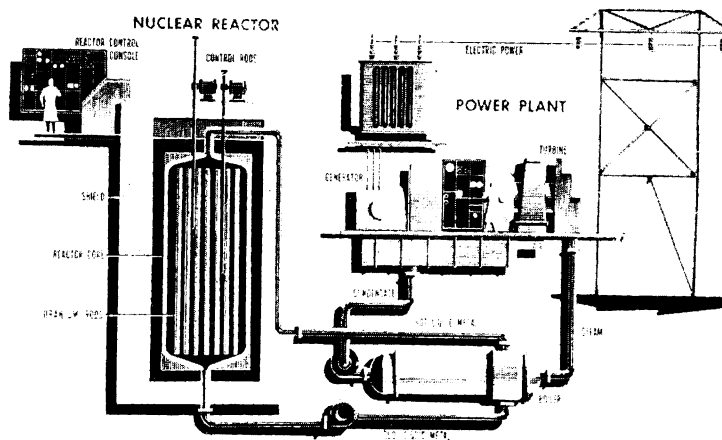


Fig. 556

Dounreay in the North of Scotland (Fig. 557). It is likely that power stations of the future will be of this type, as it has many advantages. By using enriched uranium (e.g. 75 per cent U-235 instead of 0.7 per cent) or plutonium as fuels, no moderator is required. This means that the reactor core can be reduced from about 10 metres in diameter to 1 metre. By surrounding the reactor with a blanket of natural uranium which catches any escaping neutrons plutonium can be produced (see page 226). In fact the quantity of plutonium produced in the blanket is greater than that used as fuel! Such a system is called a *breeder reactor*.

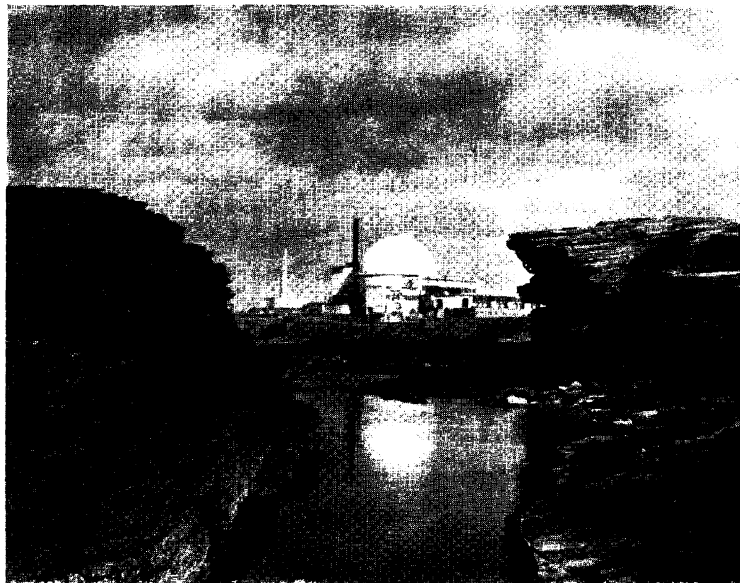


Fig. 557

Fig. 558 gives an artist's impression of the Prototype Fast Reactor now being built at Dounreay and scheduled to open in 1971. It will use mixed oxides of uranium and plutonium as fuel, and liquid sodium instead of carbon dioxide to remove the heat from the core. The reactor is expected to produce 600 megawatts of heat and 250 megawatts of electricity, a very high overall efficiency.

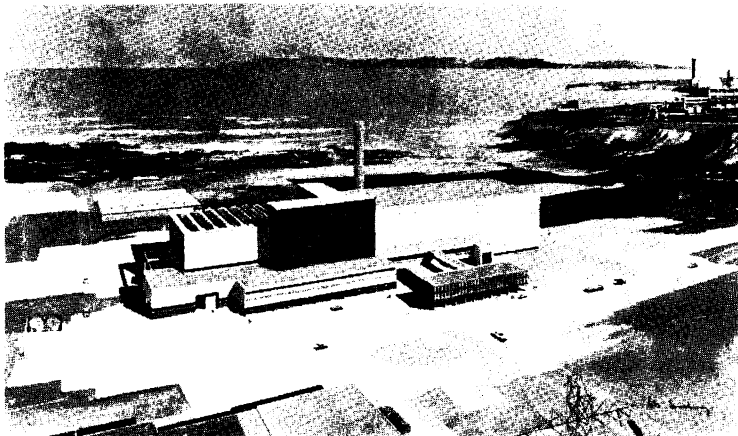


Fig. 558

By the 1970s it is expected that it will cost less to generate electricity from nuclear fuels than from coal and oil. A much more important consideration at a time when the earth's supply of fossil fuel is gradually disappearing is that fast breeder reactors will provide a source of almost limitless energy. New fissionable plutonium is produced as uranium-235 is consumed.

Nuclear Powered Vessels

America launched the first nuclear powered submarine, *Nautilus*, in 1954 (Fig. 559). She travelled 60,000 miles, using only 4 kilograms of uranium fuel. Three million gallons of oil would have

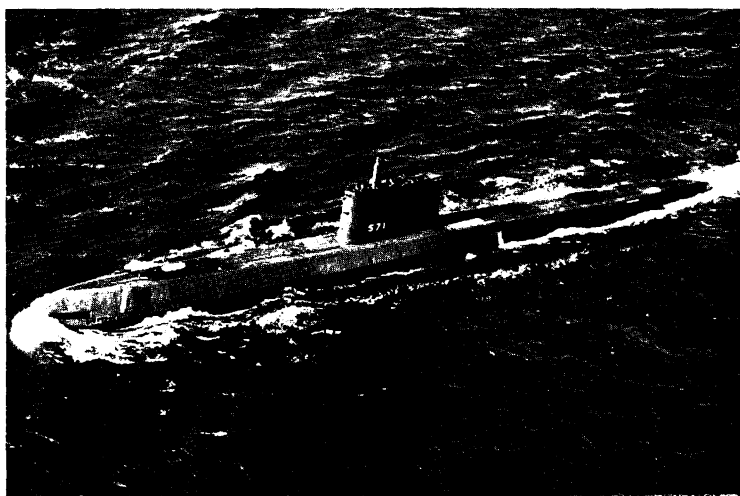


Fig. 559

been needed to cover the same distance using diesel motors. In 1958 the *Nautilus* made history by crossing beneath the North Polar ice cap. In 1960 her sister ship, *Triton*, travelled round the world submerged, a distance of 36,000 miles.

In 1957 Russia launched the first nuclear powered surface vessel, the ice-breaker *Lenin*. America's first nuclear ship, *Savannah* (Fig. 560), was used commercially for two years, but she proved uneconomical and was 'mothballed' in 1967.

A nuclear powered airship has been proposed as one way of overcoming the difficulties associated with the massive radiation shields needed in nuclear aircraft.

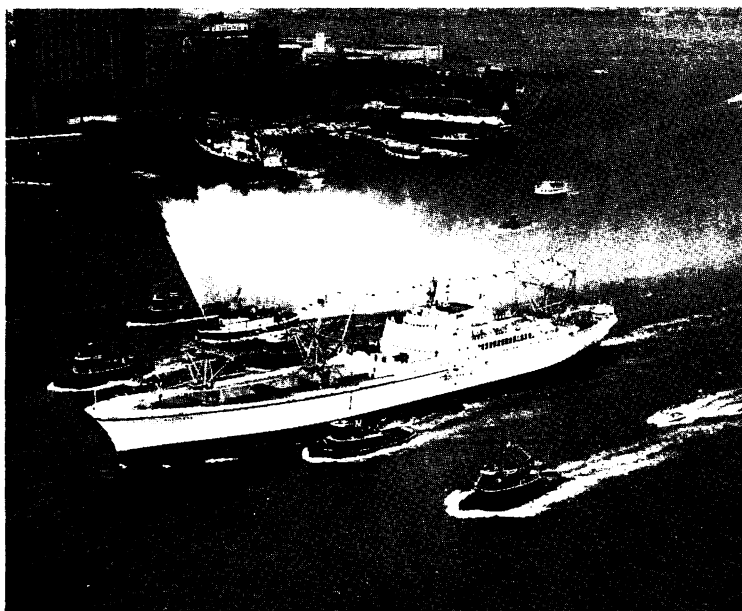


Fig. 560

Nuclear Fusion

1952

On November 1st, 1952, a small coral island with an area of 13 square miles disappeared. The first H bomb had exploded. It had five times the destructive power of all the conventional bombs dropped during the whole of World War II. Ten years later an explosion equivalent to that produced by 50 million tons of TNT announced that an even bigger H bomb had been produced.

To understand how these bombs produce such enormous quantities of energy study the graph shown in Fig. 561. It shows how the mass per nucleon in an atom varies with the atomic number. From the graph it is clear that if U-235 is split into Kr 92 and Ba 141 the mass per nucleon has *decreased*. We have seen that this decrease in mass shows itself as additional kinetic energy in the fission products. The heat produced in nuclear reactors comes from such a fission.

In 1932 Cockcroft and Walton fired a hydrogen nucleus (^1_1H) at a lithium nucleus (^7_3Li); the particles fused and then split into

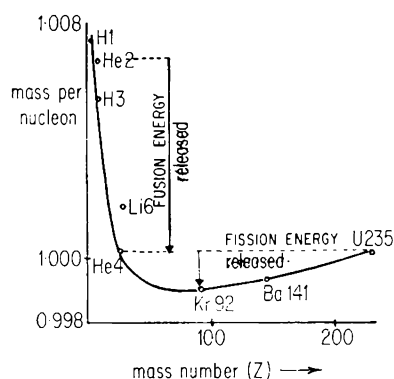
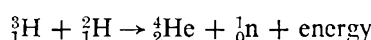


Fig. 561

two helium nuclei ($2 \times {}^4_2\text{He}$). From Fig. 561 we see that the mass per nucleon has been reduced. This decrease in mass appears as kinetic energy in the two alpha particles. The process is called nuclear fusion.

Although the fusion of a few nuclei of light elements is possible with the help of particle accelerators, large quantities of energy can be released only if millions of nuclei are fusing at once. In the hydrogen bomb the nuclei of two isotopes of hydrogen are speeded up by raising their temperature to over a hundred million degrees centigrade. The only method known at present which is capable of producing such temperatures is the fission bomb. An H bomb therefore contains a fission bomb to produce the high pressure and temperature necessary to initiate the fusion reaction. When a collision occurs between two fast moving nuclei at such temperatures, the reaction is called *thermo-nuclear fusion*.



$E = mc^2$ enables us to calculate the quantity of energy released.

$$\text{tritium } {}^3_1\text{H} = 5.00890 \times 10^{-27} \text{ kg}$$

$$\text{deuterium } {}^2_1\text{H} = 3.34441 \times 10^{-27} \text{ kg}$$

$$8.35331 \times 10^{-27} \text{ kg}$$

$$\text{helium} = 6.64632 \times 10^{-27} \text{ kg}$$

$$\text{neutron} = 1.67490 \times 10^{-27} \text{ kg}$$

$$8.32122 \times 10^{-27} \text{ kg}$$

The mass transformed is equivalent to 17.6 MeV. If 1 gramme of tritium and deuterium were fused in this way, the energy released would be adequate to supply an average household for 40 years!

In a similar reaction two deuterium nuclei can be fused to give about 5 MeV per fusion. As deuterium can be extracted very cheaply from sea water, enough energy for at least ten thousand million years is readily available! You can see then why so much thought and effort is at present concentrated in trying to find a way of producing a thermo-nuclear fusion reaction under controlled conditions. What are the difficulties?

Above a few thousand degrees centigrade, gas molecules dissociate into atoms. At temperatures around 100,000°C even atoms no longer exist; they have split into positively charged nuclei and electrons. This 'fourth state of matter', consisting of equal concentrations of positive and negatively charged ions, is called a *plasma*.

If controlled thermo-nuclear reactions are to be produced, two major problems arise. First, how can the required temperatures, which are in the region of 300,000,000°C, be achieved, and secondly how can the plasma once formed be held together (contained)? These are among the most difficult problems facing science and technology at the present moment.

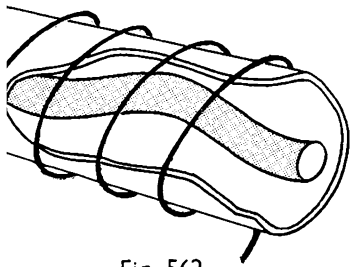


Fig. 562



Fig. 563

Let us first consider the second problem, that of containment. Clearly, as no substance can withstand such temperatures, the plasma must be kept from contact with the vessel holding it. Strong magnetic fields offer a solution—the ‘magnetic bottle’.

Charges moving quickly in the same direction in a conductor are attracted to each other. You have seen this effect with two parallel wires carrying currents in the same direction. If then a stream of ions (plasma) is moving through a tube, you might expect it to ‘pull itself together’ into a narrow beam at the centre of the tube. This is called the *pinch effect*. In practice it is about as difficult to achieve it successfully as balancing one bar magnet in mid air above another repelling magnet.

To counter this instability a coil is wrapped round the tube containing the plasma. If a current is then passed through the coil, the ions will spiral round the field lines inside the tube, thus preventing the plasma from touching the sides (Fig. 562). The Leybold tube_{N61} illustrated in Fig. 563 provides a delightful demonstration of this spiral effect with an electron beam.

In 1958 there were hopes that thermonuclear fusion had occurred in ZETA (Zero Energy Thermonuclear Assembly) at Harwell (Fig. 564). Neutrons were released, showing that fusion had

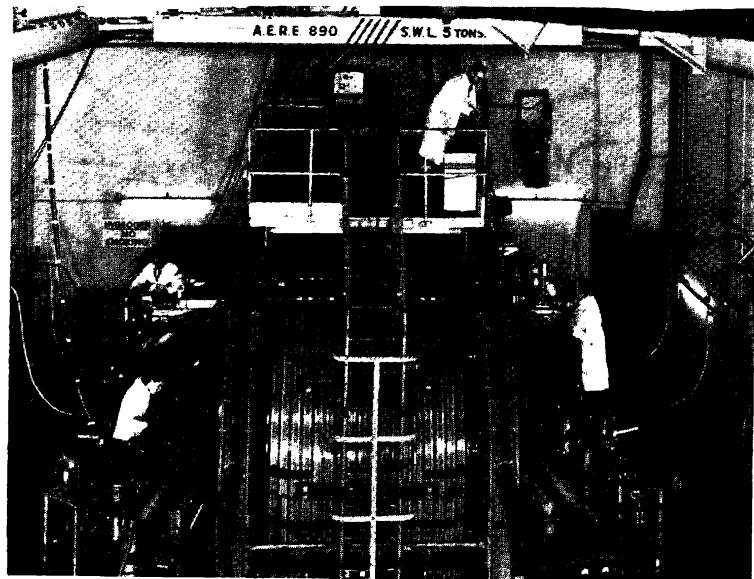


Fig. 564

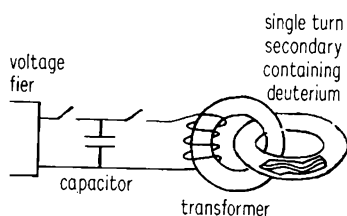


Fig. 565

occurred, but not, unfortunately, thermonuclear fusion. The high speed ions in the plasma had fused with stationary ions.

Zeta consists of a giant doughnut of about 3 metres in diameter. It contains deuterium gas, which acts as the single turn secondary of a double toroidal transformer (Fig. 565). By passing an enormous pulse of current through the primary windings, a current of the order of a million amperes flows through the deuterium. This forms a plasma at several million degrees centigrade. The giant

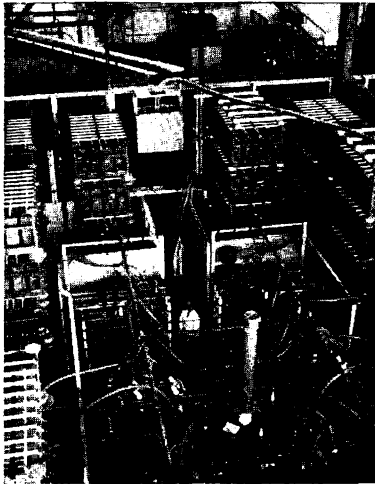


Fig. 566

pulse of current in the primary comes from capacitors which store several megajoules (Fig. 566).

Other machines which have attempted to produce thermonuclear fusion are the *Stellaratron* (Fig. 567) at Princeton University, the appropriately named *Perhapsatron* at Los Alamos and more recently ALICE (Adiabatic Low-Energy Injection and Capture Experiment) at the University of California.

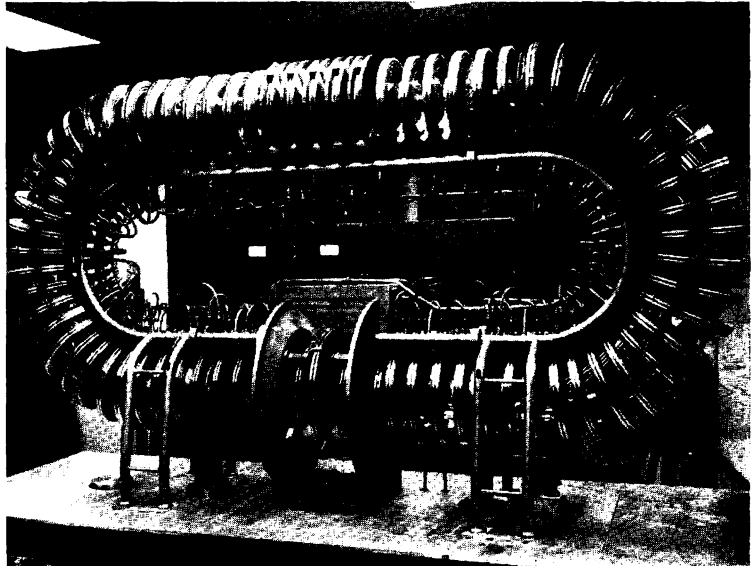
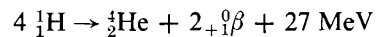


Fig. 567

All the heat produced by the sun is almost certainly due to thermonuclear fusion, which in effect produces helium from hydrogen.



The sun is estimated to be 'losing weight' at a rate of four million tons per second. By doing so it hopes to 'live' for at least another ten thousand million years!

Fundamental Particles

Forty years ago it looked as though the complex structure of matter could be reduced to three simple particles—the electron, the proton and the photon or quantum of electromagnetic radiation. In the 1930s this simple picture started to change. The positron and neutron were discovered. In 1935 the Japanese theoretical physicist Hideki Yukawa suggested that the strong forces binding the nuclear particles together might usefully be described as 'particles continually being exchanged between the nucleons'. Cecil Powell discovered such particles in cosmic radiation. They are called *pions*. The mass of each is about 270 times that of the electron.

To account for the fact that the conservation laws of energy, momentum and angular momentum do not appear to hold during the radioactive process of beta decay, another particle was 'invented' by Pauli in 1931. It was called the *neutrino*. It had to have no mass and no charge and yet be able to possess energy and momentum! Twenty-five years later the postulate was justified when Reines and Cowan obtained experimental evidence of neutrinos coming from a nuclear reactor.

Mountain tops became happy hunting grounds for particle spotters. Balloons, and more recently satellites, have also been used. Up there nature provides the most powerful atom-smashers



Fig. 568

known—the high energy protons present in cosmic radiations. Fig. 568 shows the result of a proton colliding with a nucleus in a photographic plate. Several pions are produced.

Work with cosmic radiation was not entirely satisfactory, however. The radiation was haphazard and the energy of the cosmic particles unknown. Early particle accelerators such as the Van de Graaff generator could produce voltages up to about 7 MeV, which was not enough to produce new particles by collision. 200 MeV was needed, and this seemed out of the question.

An alternative way of providing high energy particles was, however, soon developed—the particle accelerator. These machines speed up particles to very near the speed of light, and produce

energies of over a thousand million electron volts. The Brookhaven and the CERN synchrotron (Figs. 569 and 570) can each produce protons of 30 GeV (3×10^{10} eV). A proton will reach this energy in one second as it travels half a million times round the circuit. If electrons are accelerated in this way, there comes a point when they radiate as much energy as they gain each revolution. This difficulty, which is mainly caused by the circular motion of the electrons, can be minimised by using a linear accelerator (see page 15).



Fig. 569



Fig. 570

When accelerated particles reach their maximum energy, they are fired into a target to produce new particles by collision. These particles are then allowed to pass into a bubble chamber.

The chance of a nuclear collision occurring in a gas is very remote, as the molecules are so far apart. The Wilson cloud chamber is not therefore particularly well suited to the study of collisions. A liquid, on the other hand, has about one thousand times as many molecules per cubic centimetre. If, then, particles are passed into a transparent liquid, such as liquid hydrogen, a stream of bubbles may be formed under certain circumstances.

The liquid is kept under pressure at a temperature above its normal boiling point. If a charged particle is then passed through the liquid and if the pressure is reduced suddenly, a stream of tiny vapour bubbles will form on the ions produced by the particle. Fig. 571 shows a phototograph of the bubble tracks of a number of different sub-nuclear particles. If the bubble chamber, invented in 1952 by D. A. Glaser, is situated in a strong magnetic field, the curvature of the track gives a clue to the charge on the particle. The length of the track often indicates its energy or the duration of the particle's life before it decays into another particle! The expectation of life for many of the new particles is of the order of 10^{-10} seconds or less.

Fig. 571

The study of these incredible fragments of matter and anti-matter and their creation out of energy is perhaps the most exciting and the most expensive form of research at the present moment. Fig. 572 shows the bubble track of an electron and its 'anti-particle', the positron. These have been formed from a photon.

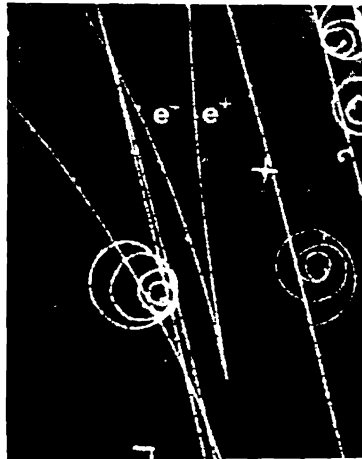


Fig. 572

America and Europe are both planning even bigger atom-smashers. A 200 GeV proton synchrotron is due for completion in Western Illinois in 1975. It will cost over £130 million to build, and need about two and a half thousand people and £20 million a year to keep it running! In Europe a 300 GeV accelerator, one and a half miles in diameter, is planned.

How many fundamental particles are there? The number depends to some extent on how you define the particles, but it is

of the order of 200. This makes nonsense of the idea of 'fundamental particles', and many attempts are being made to find a pattern into which they will fit. The more important particles in order of mass are

- (i) photons. Quanta of electromagnetic radiation.
- (ii) leptons. The electron, muon and neutrino.
- (iii) mesons. The pion and kaon.
- (iv) baryons. These are heavy particles such as the proton, neutron and a few heavier particles.

Research in fundamental particles is one of the spearheads of physics today. One interesting theory suggests that there may be particles which are more elementary than the elementary particles! These have been called *quarks*, and it has been suggested that three such particles may, when tightly bound together, produce all the fragments which are at present called 'fundamental particles'. The first man to find experimental evidence for such particles will make history!

Epilogue

During this course you have caught a glimpse of some of the exciting and challenging developments that are taking place in modern physics. These developments confront you with a double challenge: first to achieve a deeper understanding of basic physical principles, and secondly to ensure that this knowledge is used for the good of mankind in agriculture, education, industry, medicine and research. The vision of Teilhard de Chardin provides a fitting goal. 'The true physics is that which will one day achieve the inclusion of man in his wholeness in a coherent picture of the world'.

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